Physics and Performance of Ultra-High-Frequency Field-Effect Transistors

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Outline

- Introduction
- RF FET Physics and Design Rules
- Performance of RF FETs
- Options for Future RF FETs
- Conclusion

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What Does Ultra-High Frequency Mean?

In this talk: Ultra-High-Frequency = much above 1 GHz

Synonymous: - microwave electronics
- RF (radio frequency) electronics.

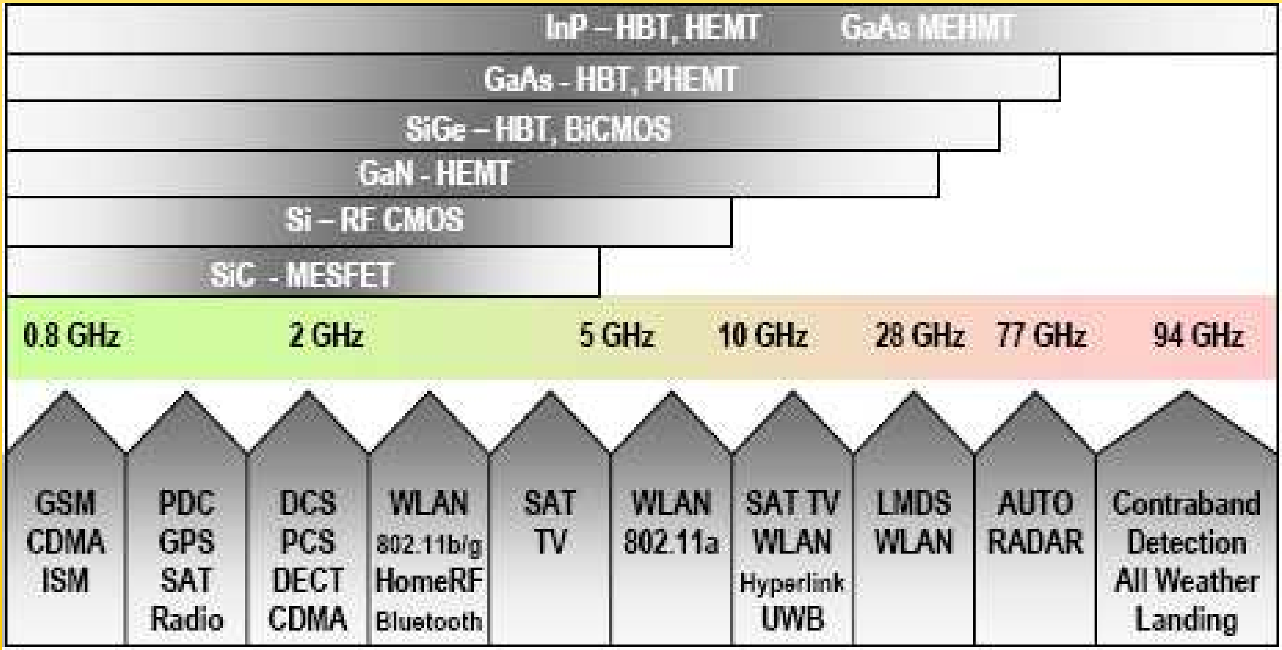
In the follwing: ultra-high-frequency = RF

Traditionally: - defense related applications clearly dominated
Currently: - large consumer markets for RF products
- defense related applications

Spectrum of civil RF applications, Ref. ITRS 2005.

Currently most civil RF applications with large-volume markets operate below 10 GHz.

Future applications at higher frequencies are envisaged.

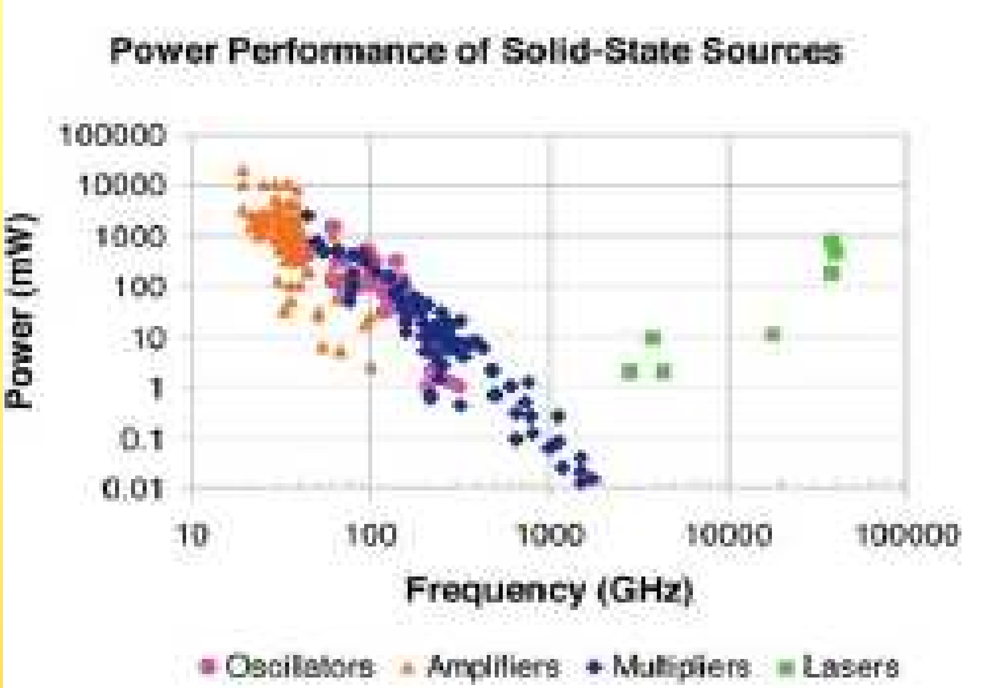


Are There Applications Beyond 94 GHz?

The THz gap: 300 GHz … 3 THz.

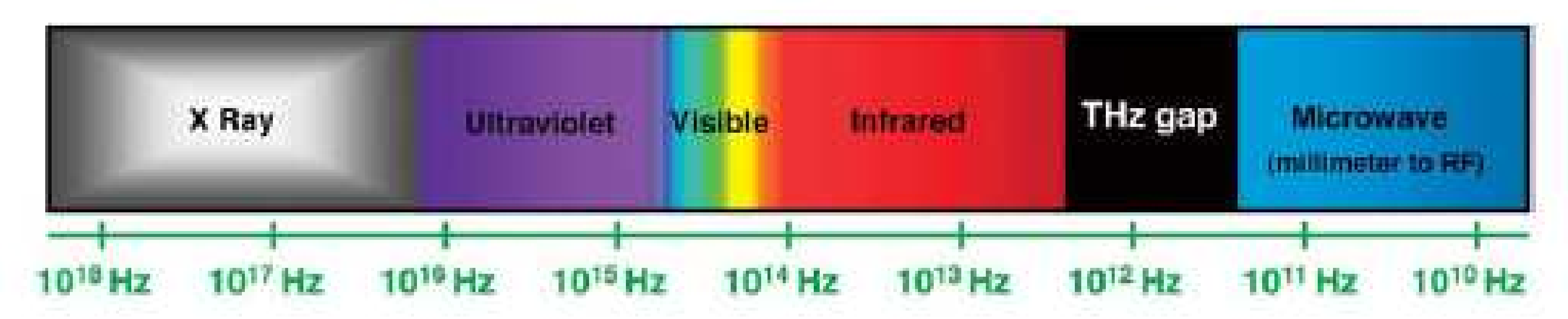
Output power of RF sources

Ref.: D. L. Woolard et al., Proc IEEE Oct. 2005.



Examples for applications in the THz gap:

- ultrafast information and communication technology
- security (detection of weapons and explosives)
- medicine (e.g. cancer diagnosis)
- …



RF transistors providing useful gain and output power in the THz gap are highly desirable.

RF Electronics vs. Mainstream Electronics

Mainstream electronics (processors, ASICs, memories)

Semiconductors

- Si

Transistor Types

- MOSFETs
- For a few applications BJTs

RF electronics

Semiconductors

- III-V compounds based on GaAs and InP
- Si and SiGe
- Wide bandgap materials (SiC and III-nitrides)

Transistor Types

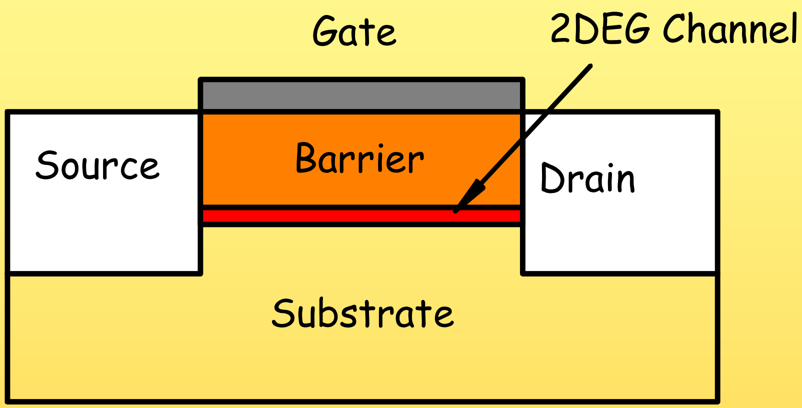
- MESFET - Metal Semiconductor FET
- HEMT - High Electron Mobility Transistor
- MOSFET - Metal Oxide Semiconductor FET
- HBT - Heterojunction Bipolar Transistor
- BJT - Bipolar Junction Transistor

RF FET Types

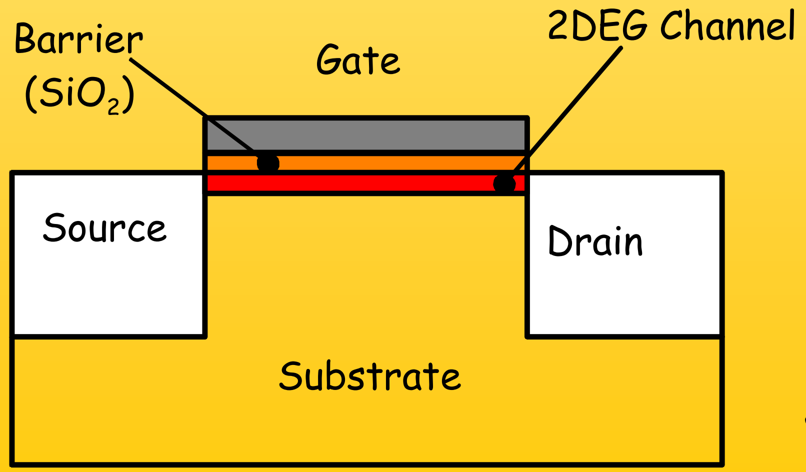
For ultra-high-frequency relevant: HEMT and MOSFET

Common feature - layer sequence in the active region:

- gate
- barrier
- 2DEG channel
- substrate

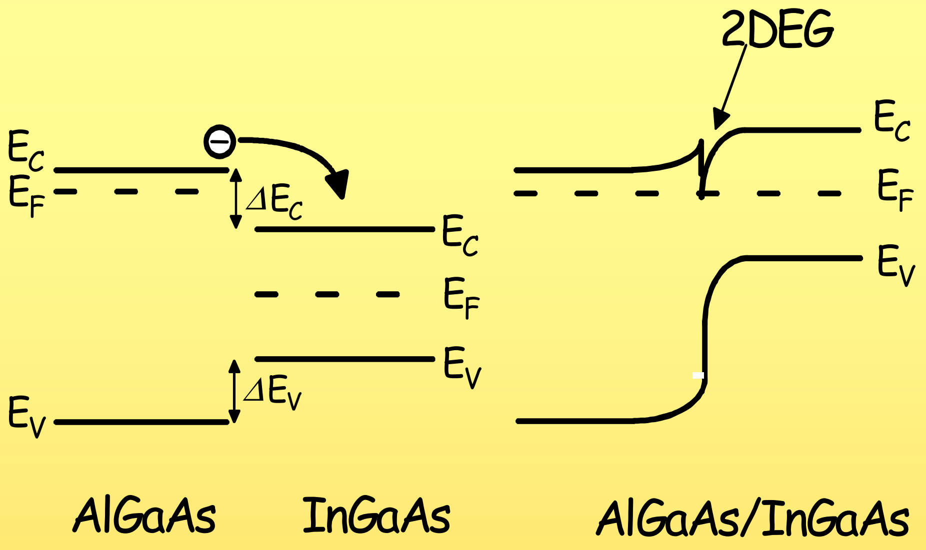


HEMT

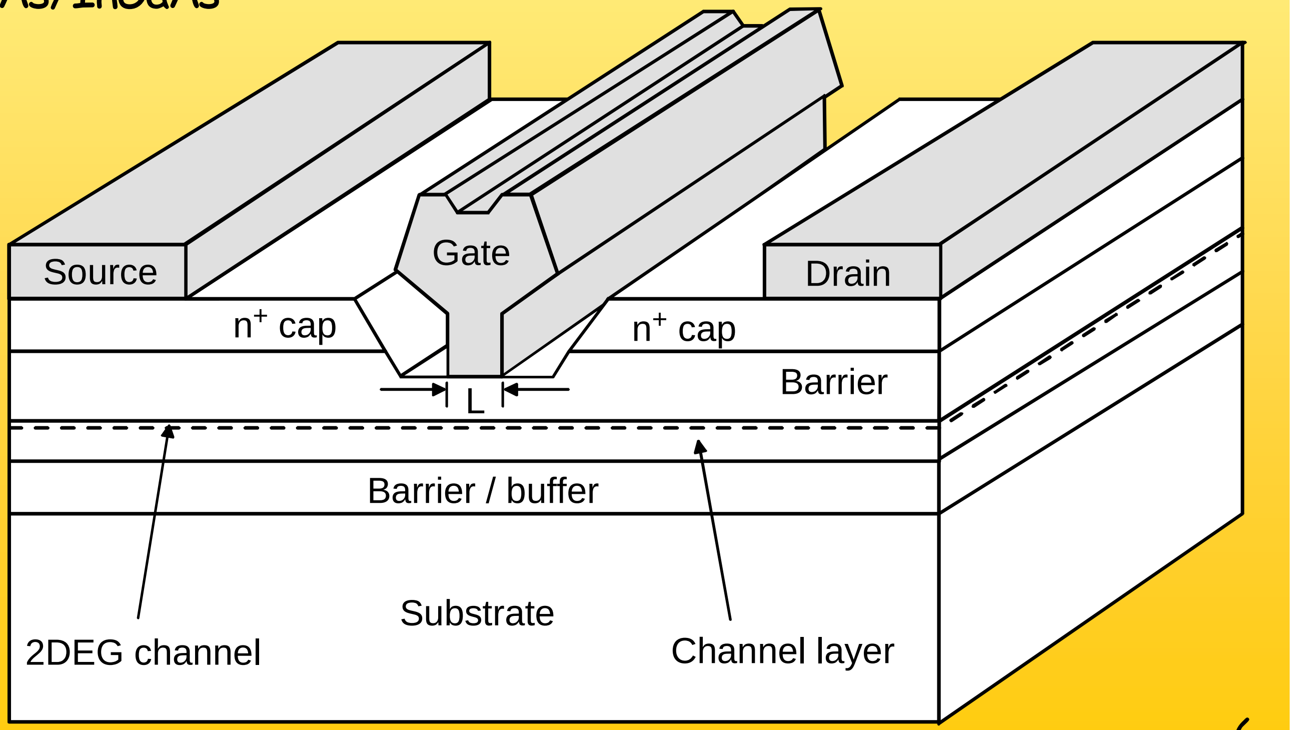


Si MOSFET

RF FET Types



Band diagram of an AlGaAs/InGaAs heterojunction as used in GaAs pHEMTs



Schematic of a HEMT High Electron Mobility Transistor

RF FET Types

FET Type	Barrier	Channel	Substrate
Conventional GaAs HEMT	AlGaAs	GaAs	GaAs
GaAs pHEMT (p = pseudomorphic)	AlGaAs	$In_xGa_{1-x}As$ $x \sim 0.2$	GaAs
GaAs mHEMT (m = metamorphic)	InAlAs	$In_xGa_{1-x}As$ $x \geq 0.53$	GaAs
InP HEMT	InAlAs	$In_xGa_{1-x}As$ $x \geq 0.53$	InP
GaN HEMT	AlGaN	GaN	SiC, Sapphire, Si
Si MOSFET	SiO_2	Si	Si

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RF Transistor Figures of Merit

Power gain G

General definition:

$$G = \frac{P_{out}}{P_{in}}$$

In RF electronics - several power gain definitions.
Frequently used: unilateral power gain U.

$$U = \frac{\left| y_{21} - y_{12} \right|^{2}}{4 \left[Re\left(y_{11}\right) \; Re\left(y_{22}\right) - Re\left(y_{12}\right) Re\left(y_{21}\right) \right]}$$

Current gain h_{21}

General definition:

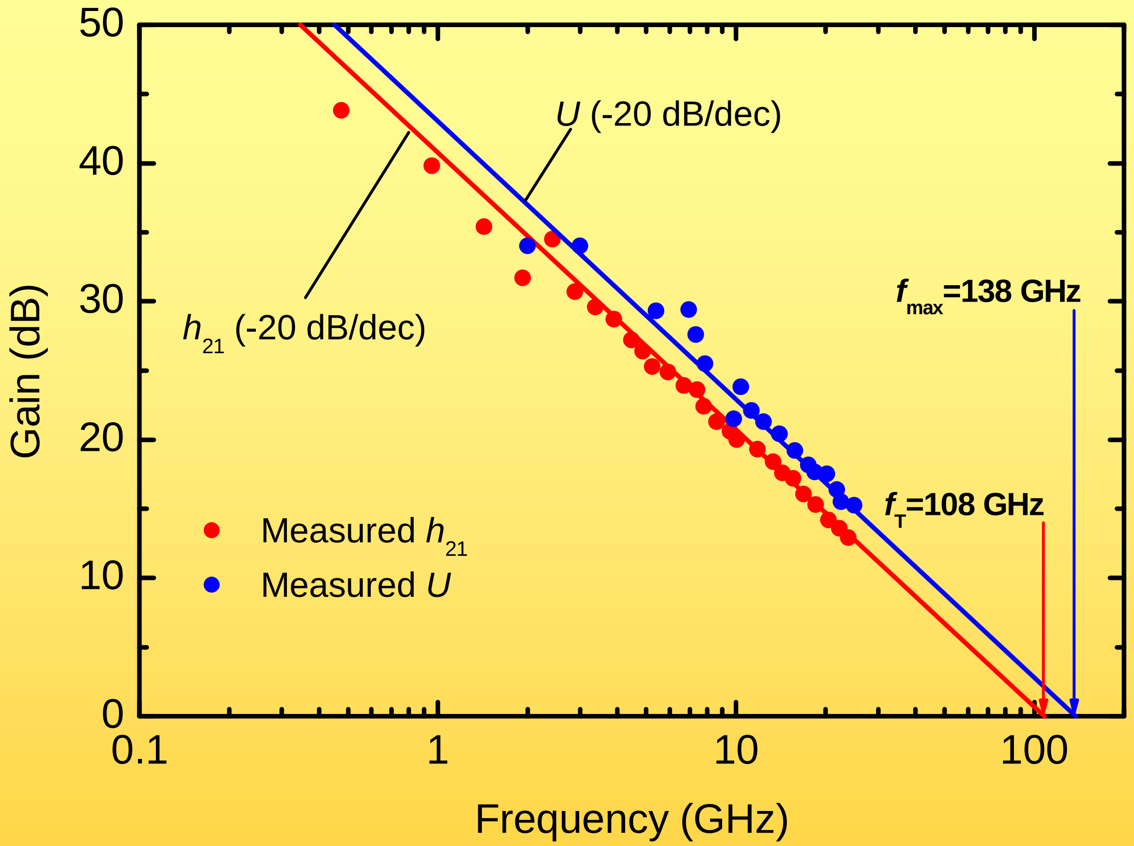
$$\left| h_{21} \right| = \left| \frac{i_2}{i_1} \right| = \left| \frac{y_{21}}{y_{11}} \right|$$

Note: gains are usually given in dB

$$Power \;\; Gain \left[dB \right] = 10 \log \left(Power \;\; Gain \right)$$

$$h_{21} \left[dB \right] = 20 \log h_{21}$$

The Characteristic Frequencies f_T and f_{max}



h_{21} and U of a GaAs RF FET
After K. Onodera et al., TED 38, p. 429.

h_{21} and U roll off at higher frequencies at a slope of approx. –20 dB/dec.

Cutoff Frequency f_T
Frequency, at which the magnitude of h_{21} rolls off to 1 (0 dB).

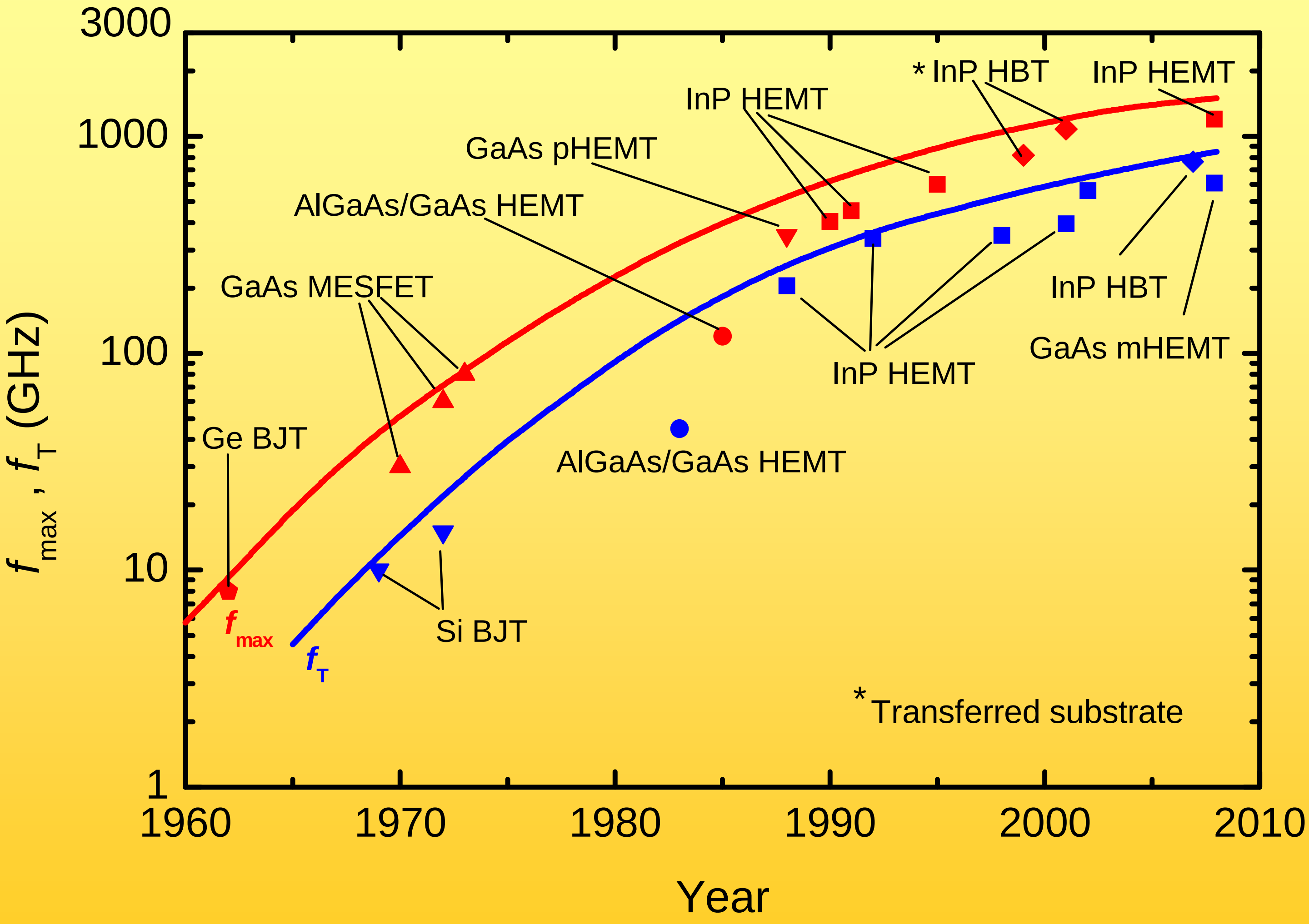
Max. Frequency of Oscillation f_{max}
Frequency, at which U rolls off to 1 (0 dB).

Rule of thumb:

- f_T should be 5 … 10 × the operating frequency f_{op} of the system in which the transistor is to be used.
- f_{max} should be around or larger than f_T.

All discussions in this talk will be restricted to f_T and f_{max}.

Evolution of f_T and f_{max}



Evolution of f_T and f_{max}

- f_T and f_{max} have been increased continuously.
- Record performance of RF FETs (Feb'08):
  - f_T 610 GHz
    Yeon et al. IEDM 2007
  - f_{max} 1.2 THz
    Lai et al. IEDM 2007

Research priority for RF transistors defined in the 2007 ENIAC SRA:
Extend III/V and SiGe technologies up to 1 THz.

RF FET Physics and Design Rules

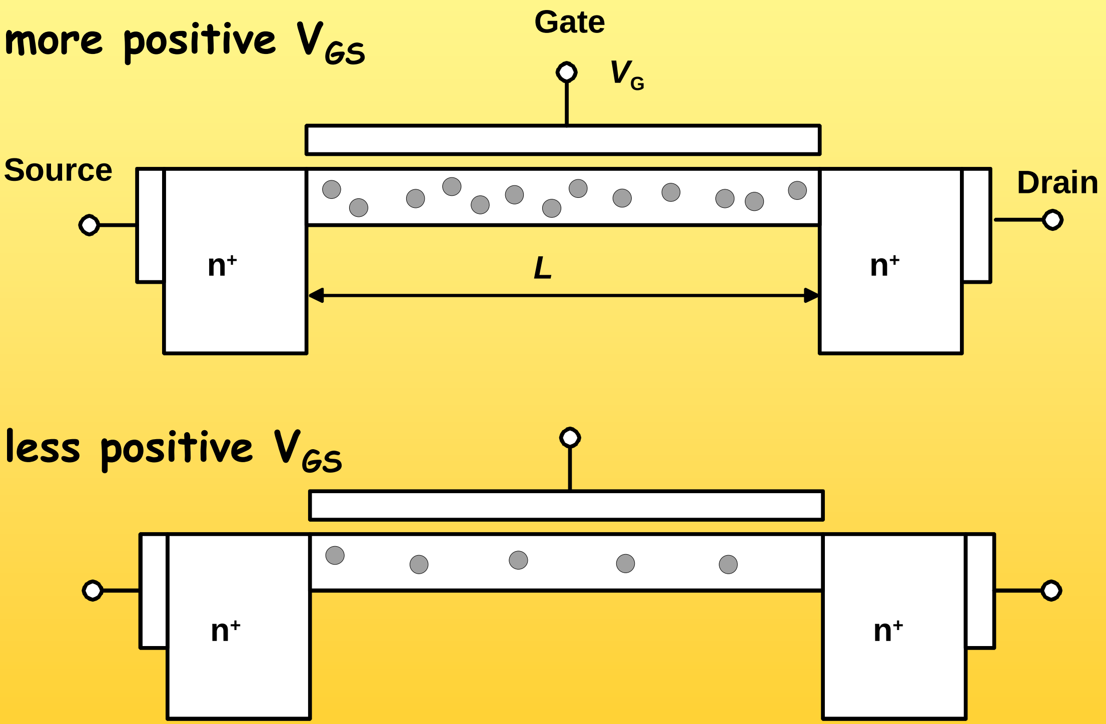
Traditional opinion:

- Si is a "slow" material, Si MOSFETs are slow.
- III-Vs are "faster" materials and III-V HEMTs are fast.
- Key to get a fast FET:
  - make the gate as short as possible,
  - take the material with the highest mobility for the channel.

We will clarify if this traditional opinion is still correct.

RF FET Physics and Design Rules
- Intuitive Approach -

How to make a FET fast?



These rules are helpful but we need to take a closer look on FET physics !

RF FETs have to react fast on variations of the input signal (gate-source voltage V_{GS}).

The charge distribution in the the channel has to be changed fast.

To achieve this we have to consider

- Transistor design
  - Short channel, small L
  - Fast carriers (n-channel)
  - Minimized parasitics.
- Material issues
  - Fast carriers (high mobility, high velocity).

RF FET Physics and Design Rules
- More Detailed Approach -

Methodology

Equivalent FET Circuit

↓

Expressions for f_T and f_{max}

↓

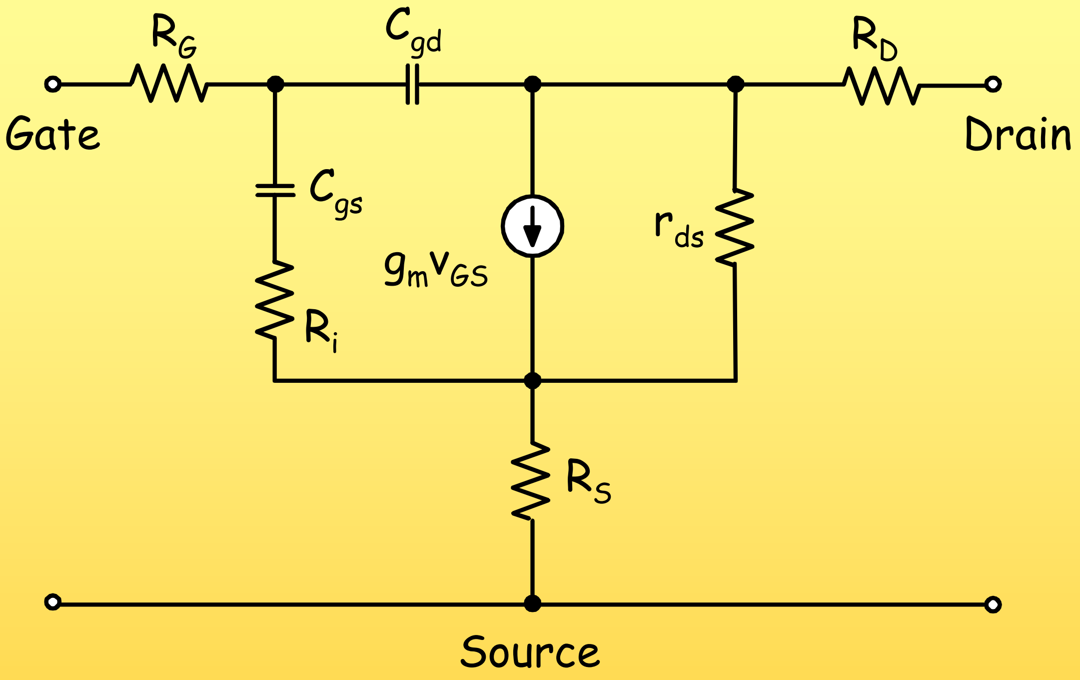
How do the circuit elements affect f_T and f_{max}

↓

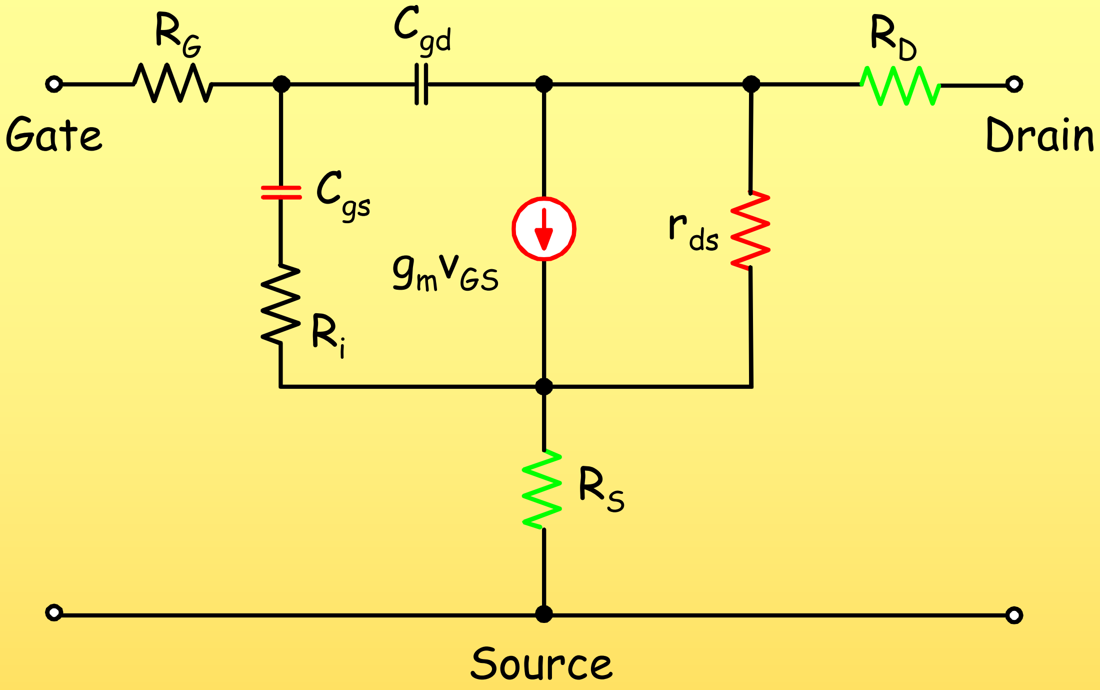
Influence of
- design features, dimensions
- material properties

on circuit elements, f_T, f_{max}

→ Compare different RF FET types



FET Equivalent Circuit



Approximations for f_T and f_{max}

$$(1) \quad f_T \approx \frac{g_m}{2\pi C_{gs}}$$

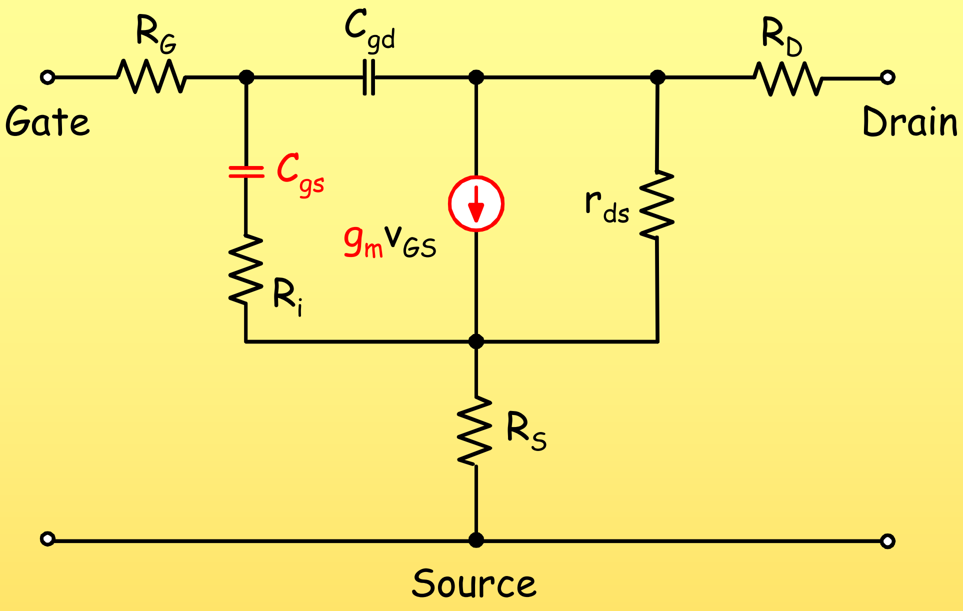
$$(2) \quad f_T \approx \frac{v}{2\pi L}$$

$$(3) \quad f_T \approx \frac{g_m}{2\pi} \frac{1}{\left[C_{gs} + C_{gd}\right]\left[1 + g_{ds}\left(R_S + R_D\right)\right] + C_{gd}\, g_m \left(R_S + R_D\right)}$$

$$(4) \quad f_{\max} \approx \frac{f_T}{2\left[g_{ds}\left(R_i + R_S + R_G\right) + 2\pi f_T R_G C_{gd}\right]^{1/2}}$$

(1), (3), and (4) suggest: - g_m should be large
- all other elements should be small

Transconductance and Gate-Source Capacitance (1)



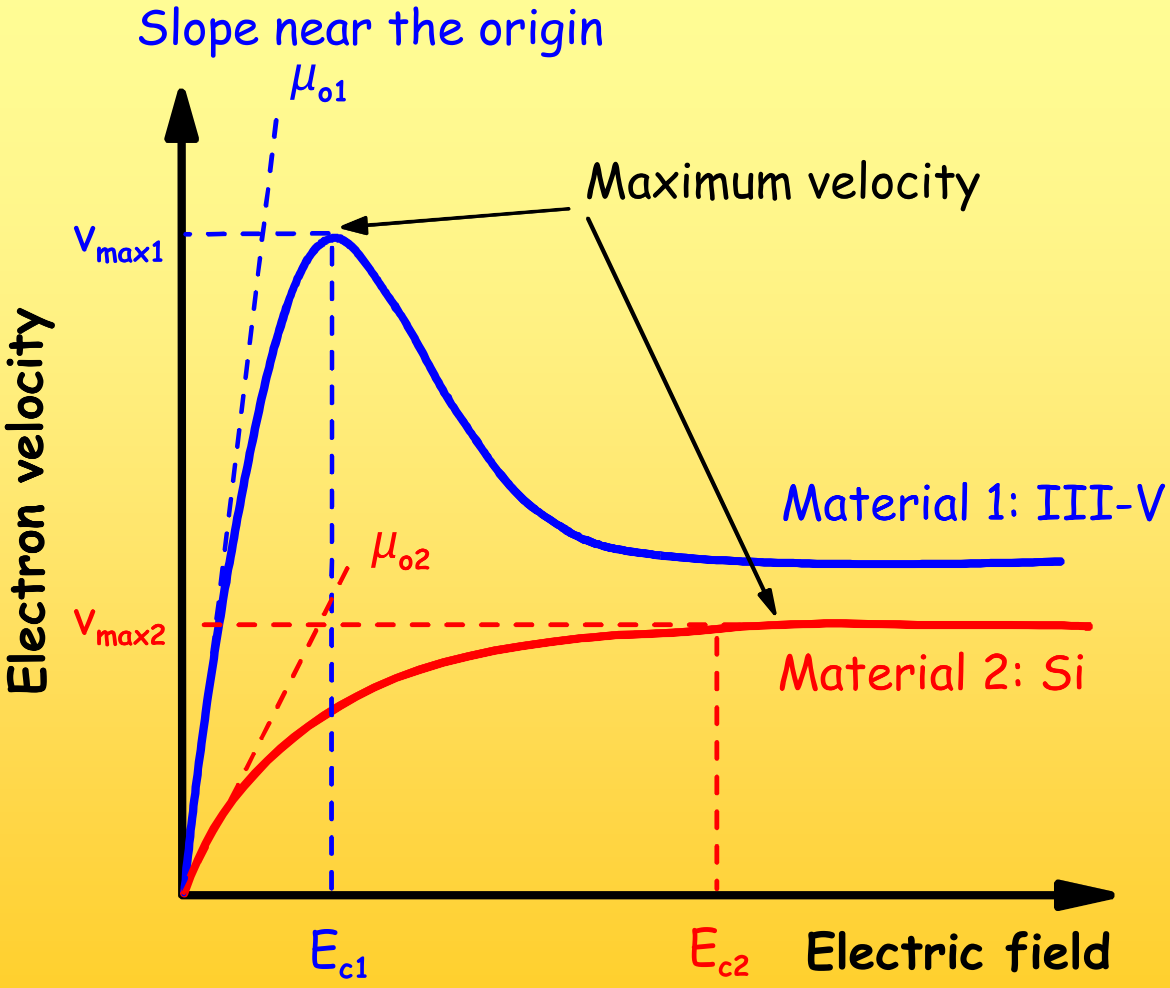
$$I_D = q\, n_{sh}\, v\, W$$

$$g_m = \frac{d\, I_D}{d\, V_{GS}} = q \frac{d\, n_{sh}}{d\, V_{GS}} v\, W$$

$$C_{gs} = -\frac{d\, Q_{ch}}{d\, V_{GS}} = q \frac{d\, n_{sh}}{d\, V_{GS}} L\, W$$

Large g_m:	- large dn_{sh}/dV_{GS}, large v.
Small C_{GS}:	- small L.
	- BUT: for a given gate length we need a LARGE intrinsic C_{GS}.

Carrier Transport

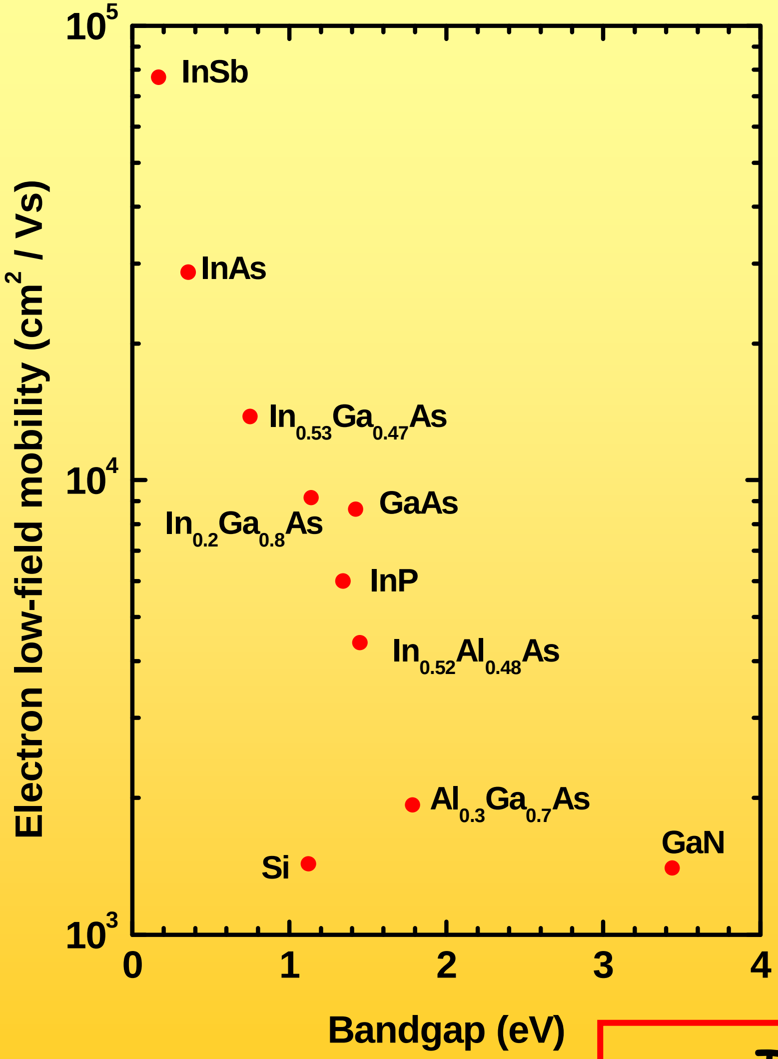


Stationary velocity-field characteristics

3 Figures of Merit
- low-field mobility μ_0
- maximum velocity v_{max}
- critical field E_c

Desirable for high g_m
- high μ_0
- high v_{max}
- small E_c

Carrier Transport (Low-Field)



Low-field mobility vs bandgap
(undoped bulk material, 300 K)

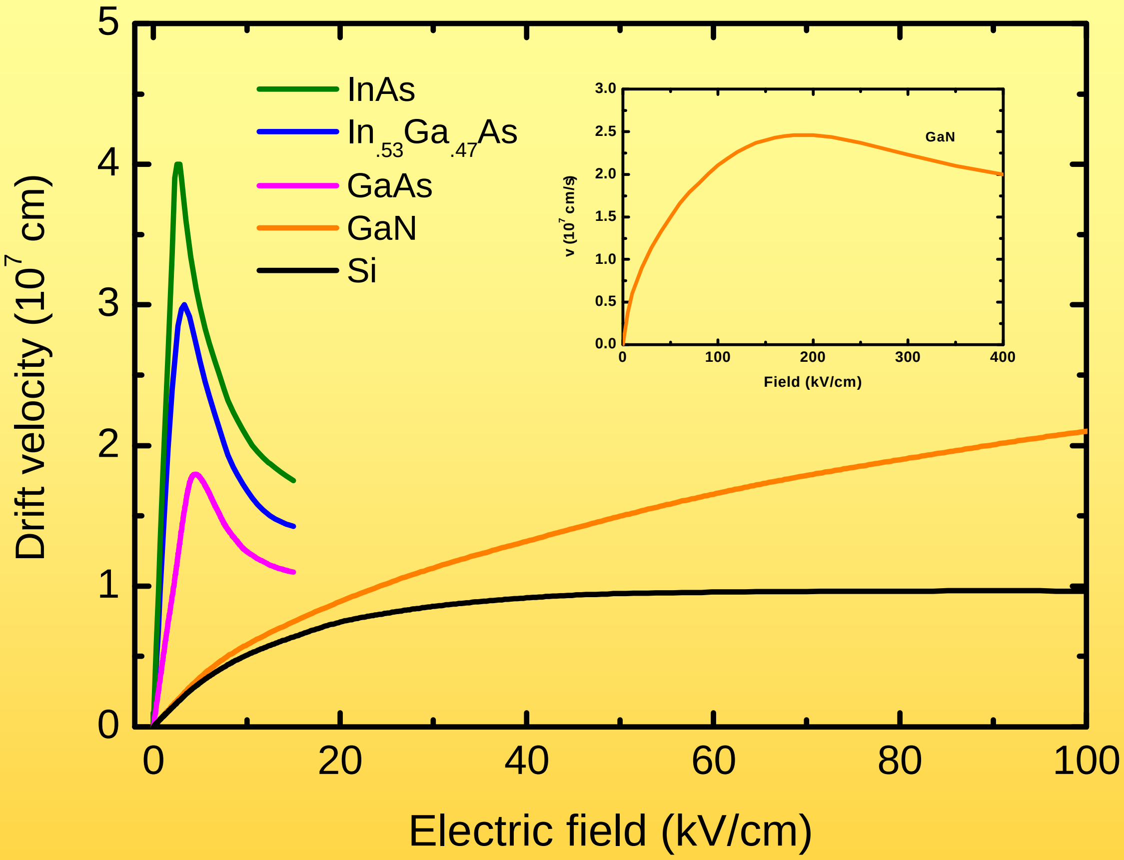
Trend:
High mobility – narrow bandgap

Problems of narrow bandgap materials
- low breakdown field
- high intrinsic carrier concentration

$$n_i \propto \exp -\frac{E_G}{2\,k_B\,T}$$

Intermediate conclusion regarding μ_o:
narrow/medium bandgap III-Vs have an edge.

Carrier Transport (High-Field)



Trend:
Narrow bandgap – high v_{max} and small E_c

Intermediate conclusion regarding v_{max} and E_c: III-Vs have an edge.

Velocity-field characteristics

Gate Modulation Efficiency (dn_{sh}/dV_{GS})

- Gate modulation efficiency is related to the density of states DOS in the conduction band
- The DOS is related to the effective mass

Material	m^*_{DOS} (bulk)
Si	1.18
InAs	0.031
$In_{0.53}Ga_{0.47}As$	0.048
GaAs	0.067

- Large m^*_{DOS} – large gate modulation efficiency

Intermediate conclusion regarding DOS:
Si has an edge.

Transconductance and Gate-Source-Capacitance (2)

$$(1) \quad f_T \approx \frac{g_m}{2\pi C_{gs}} = \frac{g_m}{2\pi\left(C_{gs,\mathrm{int}} + C_{gs,par}\right)}$$

$$C_{gs,\mathrm{int}} = q\,\frac{d\,n_{Sh}}{d\,V_{GS}}\,L\,W \approx \frac{\varepsilon_{bar}\,L\,W}{d_{bar}}$$

$C_{gs,par}$: fringing, stray, pad capacitance components

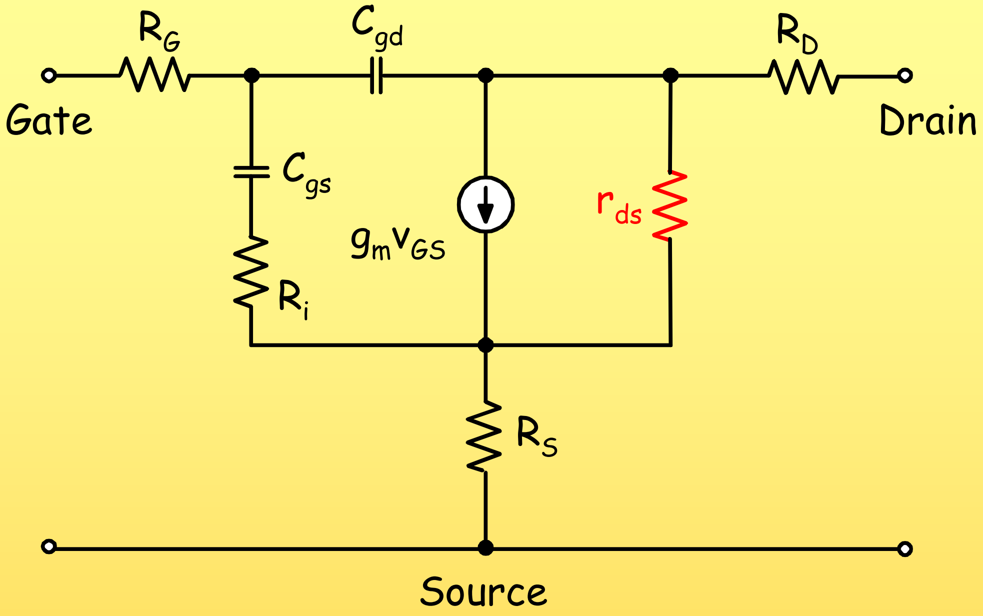
$$f_T \approx \frac{g_m}{2\pi\left(\dfrac{\varepsilon_{bar}\,L\,W}{d_{bar}} + C_{gs,par}\right)}$$

Desirable: $C_{gs,int} \gg C_{gs,par}$
i.e., large $\varepsilon_{bar}/d_{bar}$

Transistor Type	Barrier	$\varepsilon_{r,bar}/d_{bar}$ (1/nm)
GaAs pHEMT	AlGaAs	12/30 $\approx$ 0.4
InP HEMT	$In_{0.52}Al_{0.48}As$	12.7/15 $\approx$ 0,85
Si MOSFET	SiO_2	3.9/1 $\approx$ 4

Intermediate conclusion regarding $C_{gs,int}$ - $C_{gs,par}$: Si MOSFETs have an edge.

Drain Conductance



$$g_{ds} = \frac{d\,I_D}{d\,V_{DS}} = \frac{1}{r_{ds}}$$

g_{ds} - slope of the I_D-V_{DS} characteristics

$$(3) \quad f_T \approx \frac{g_m}{2\pi} \frac{1}{\left[C_{gs}+C_{gd}\right]\left[1+\underset{\uparrow}{g_{ds}}\left(R_S+R_D\right)\right]+C_{gd}\,g_m\left(R_S+R_D\right)}$$

$$(4) \quad f_{\max} \approx \frac{f_T}{2\left[\underset{\uparrow}{g_{ds}}\left(R_i+R_S+R_G\right)+2\pi f_T R_G C_{gd}\right]^{1/2}}$$

$\boxed{g_{ds} \text{ should be small}}$

Drain Conductance

Short channel effects: V_{Th} roll-off, DIBL, high drain conductance

Measure for short-channel effects: Scale length Λ (should be small).
Different scale lengths have been proposed, e.g.

- Λ_1

$$0 = \varepsilon_{ch} \tan\frac{\pi t_{bar}}{\Lambda_1} + \varepsilon_{bar} \tan\frac{\pi t_{ch}}{\Lambda_1}$$

D. Frank et al., EDL 19
pp. 385-387, 1998

$L/\Lambda_1 \geq (1.5 \ldots 2)$: short-channel effects are tolerable

- Λ_2

$$\Lambda_2 = \sqrt{\frac{\varepsilon_{ch}}{\varepsilon_{bar}} t_{ch} t_{bar}}$$

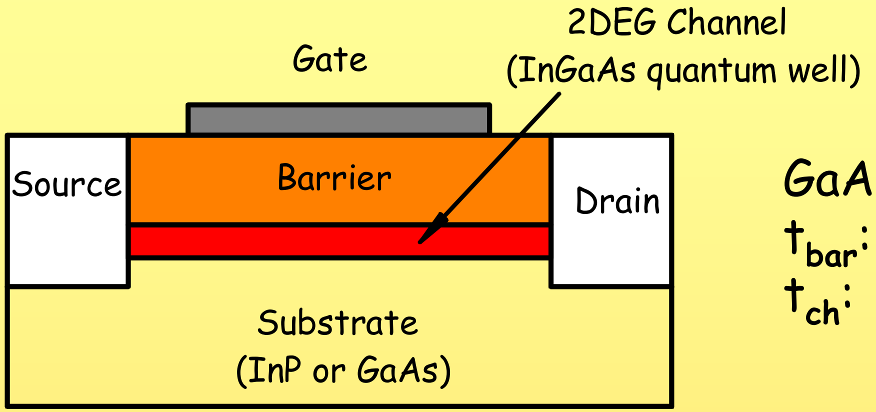
R.-H. Yan et al., TED 39
pp. 1704-1710, 1992)

$L/\Lambda_2 \geq (5 \ldots 10)$: short-channel effects are tolerable

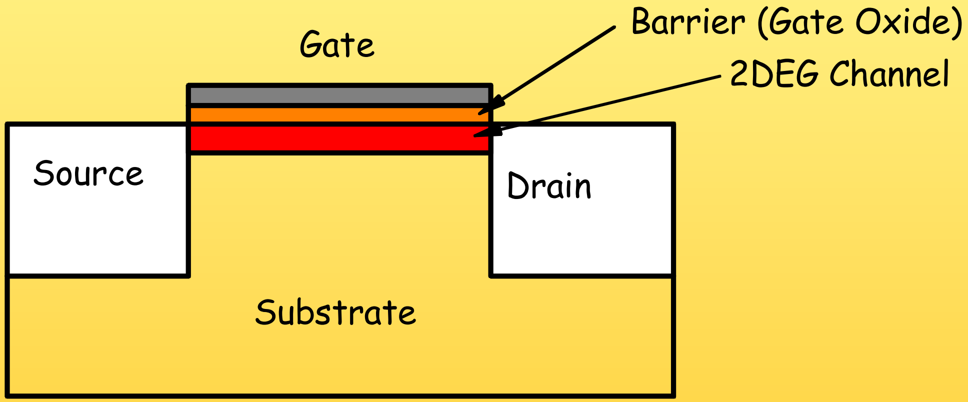
ε_{ch}, t_{ch}	dielectric constant and thickness of channel layer
ε_{bar}, t_{bar}	dielectric constant and thickness of barrier layer

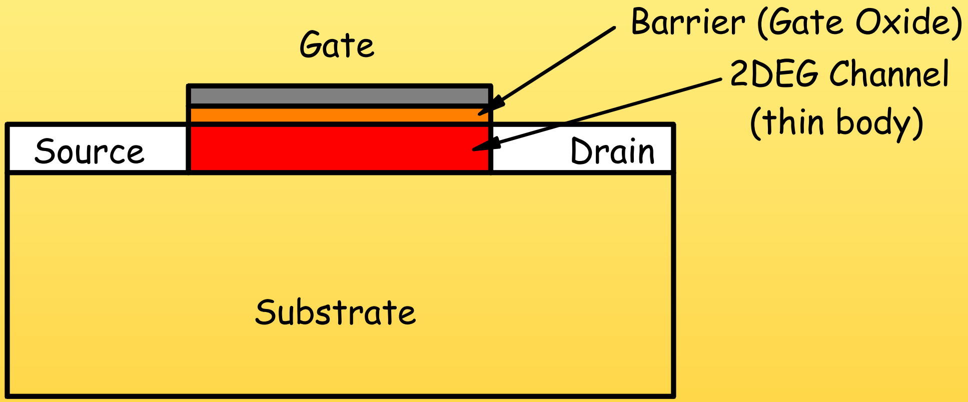
Note: scale lengths expressions have originally been developed for Si MOSFETs

Drain Conductance



GaAs and InP HEMT
t_{bar}: thickness of AlGaAs or InAlAs barrier
t_{ch}: thickness of InGaAs quantum well





Si bulk MOSFET
t_{bar}: thickness of gate oxide
t_{ch}: thickness of inversion channel
and depletion region underneath

Si SOI MOSFET (fully depleted)
t_{bar}: thickness of gate oxide
t_{ch}: thickness of Si body

Similar structure of the RF FET types: The scale length concept should be applicable to MOSFETs and HEMTs.

Drain Conductance – Scale Length

FET Type	$\varepsilon_{r,ch}$	$\varepsilon_{r,bar}$	t_{ch}	t_{bar}	Λ_1	L_1	Λ_2	L_2
GaAs pHEMT	13.3	12	15	30	44	78	22	112
InP HEMT	14.1	12.7	10	15	25	43	13	65
GaAs mHEMT	14.1	12.7	10	15	25	43	13	65
Si MOSFET	11.9	3.9	5	1	7	13	4	20
			10	1	13	22	6	28
			20	1	23	40	8	39

GaAs pHEMT — $In_{0.2}Ga_{0.8}As$ channel, $Al_{0.3}Ga_{0.7}As$ barrier

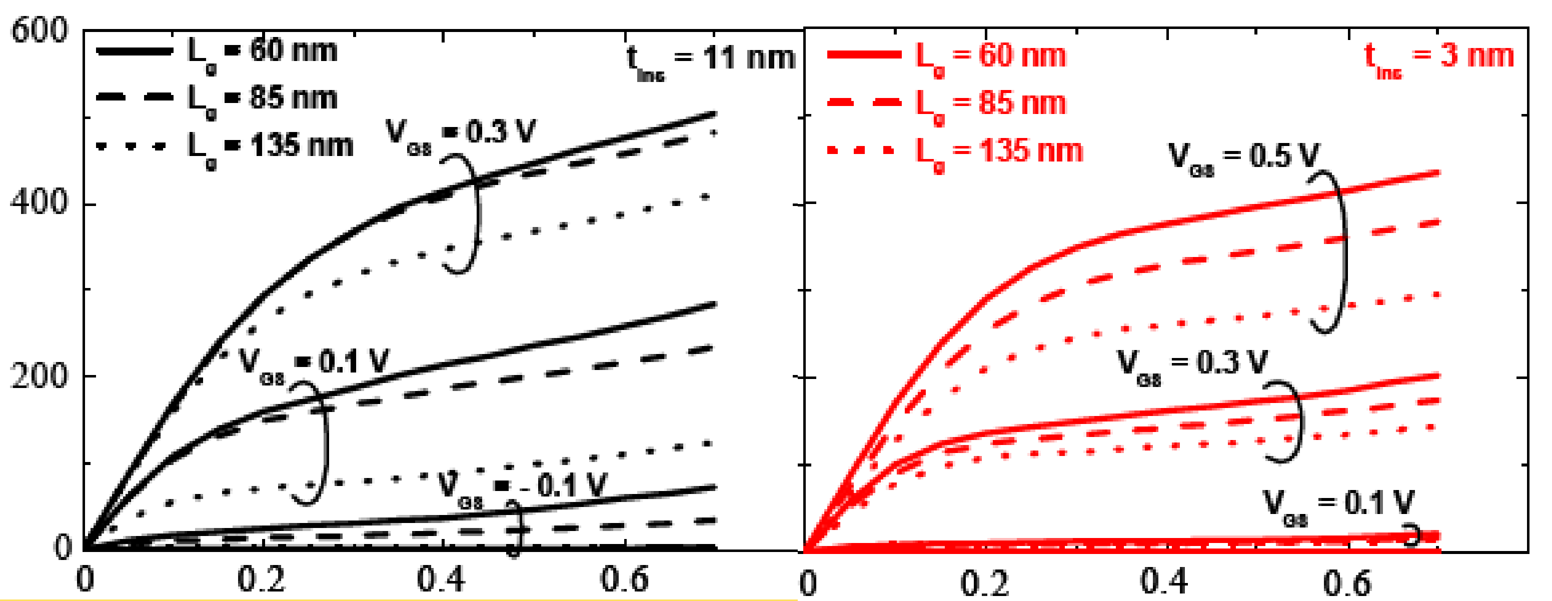
GaAs mHEMT, InP HEMT — $In_{0.53}Ga_{0.47}As$ channel, $In_{0.52}Al_{0.48}As$ barrier

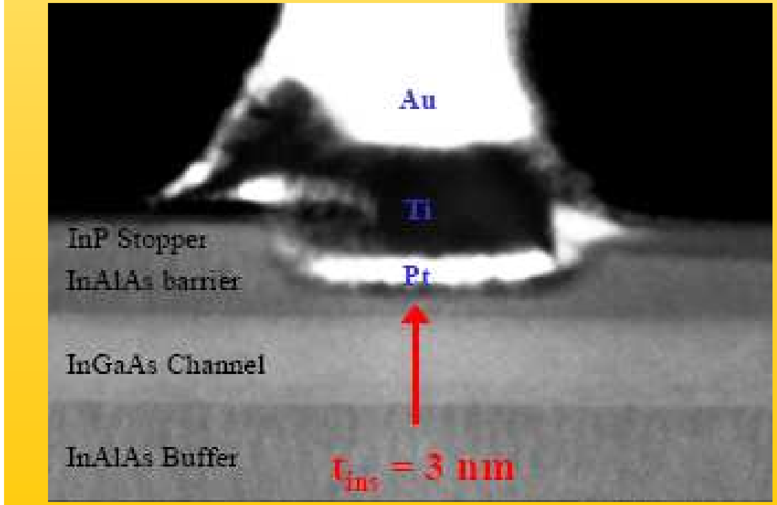
Gate lengths for tolerable sh-ch effects: $L_1 = 1.75 \times \Lambda_1$, $L_2 = 5 \times \Lambda_2$

Intermediate conclusion:
Thanks to its extremely thin barrier the Si MOSFET has an edge.
More general: the MOSFET concept has an edge.

Drain Conductance – Scale Length

InP HEMTs with extremely thin barrier (del Alamo, IEDM 2006)





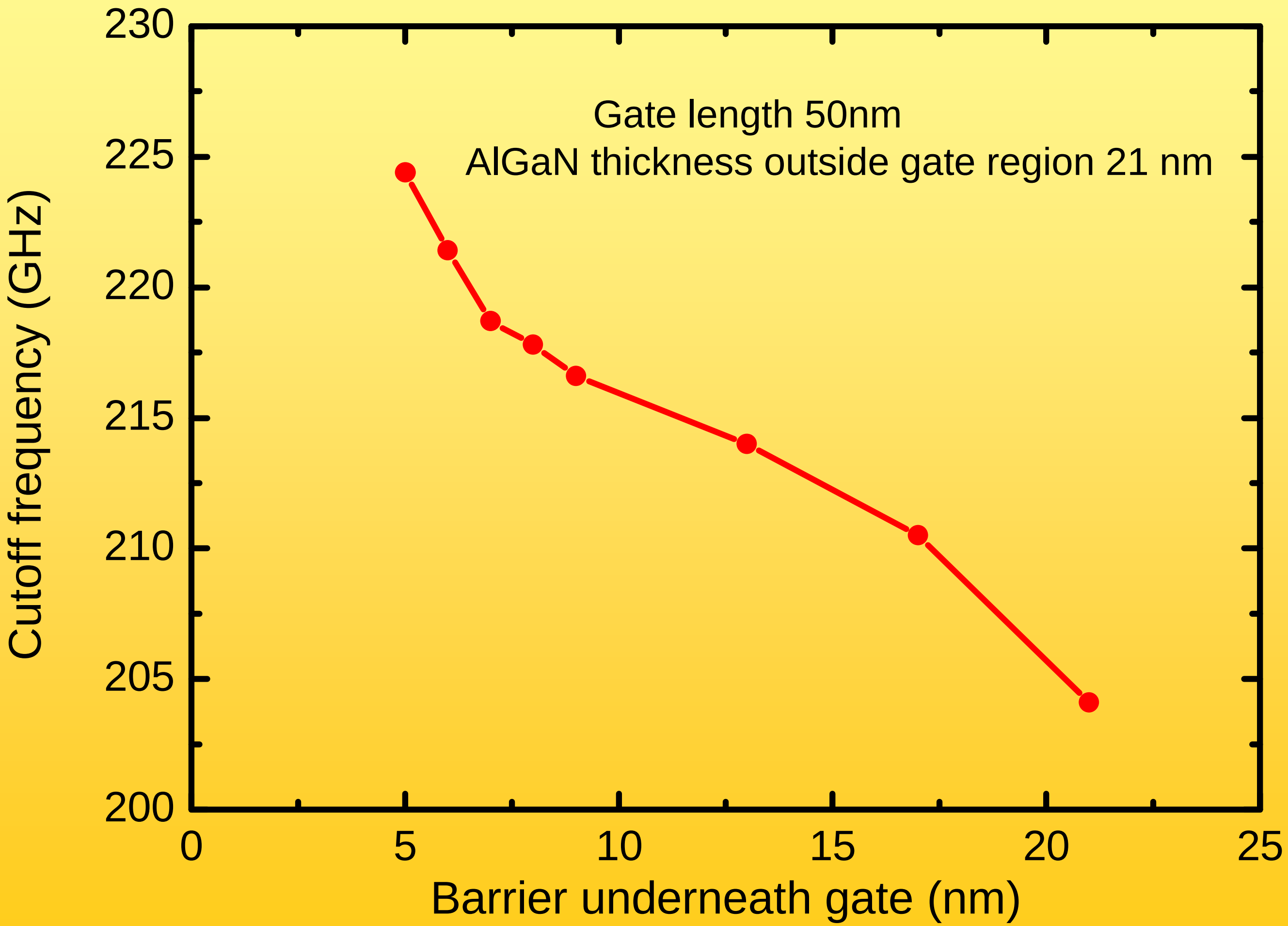
t_{bar} 3 nm
t_{ch} 10 nm

Exp. results for L = 60 nm

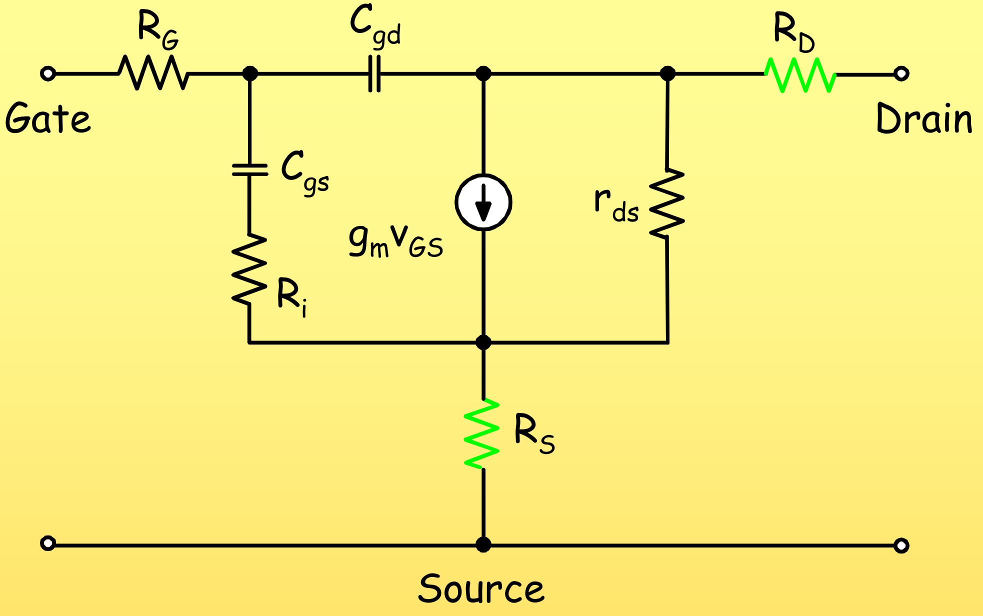
t_{bar} (nm)	11 nm	3 nm
g_{ds} (mS/mm)	332.5	192
f_T (GHz)	268	316

Drain Conductance – Scale Length

Simulated f_T of GaN HEMTs vs barrier thickness
(Schippel and Schwierz 2008, unpublished)



Source and Drain Series Resistances



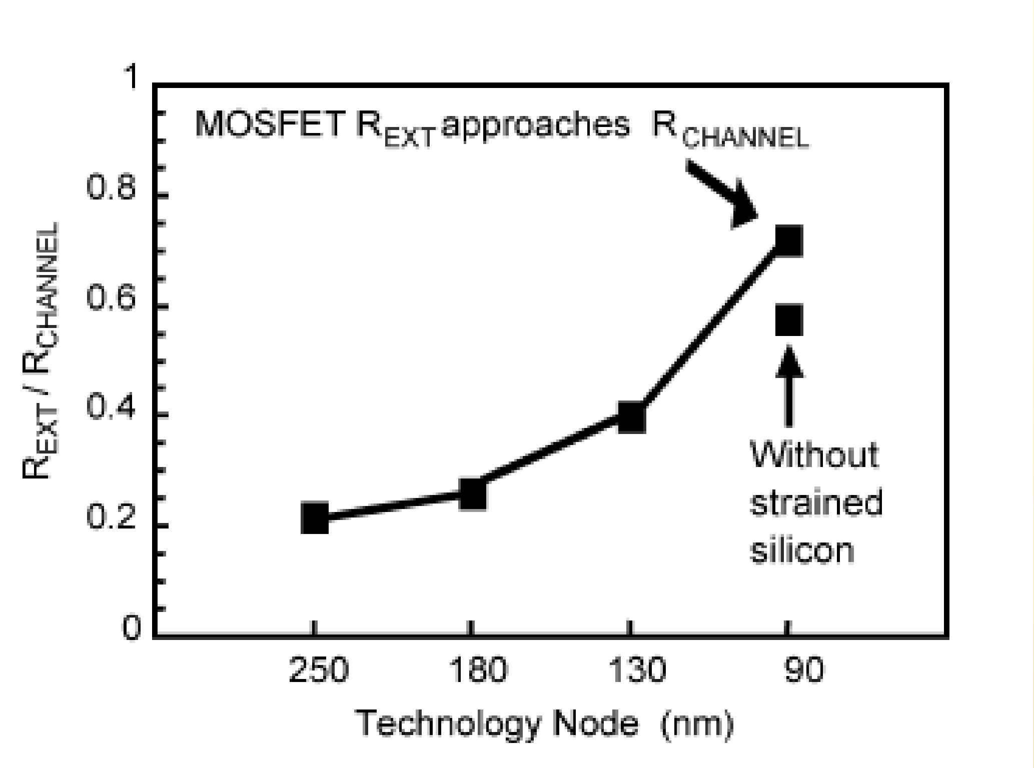
$$(3) \quad f_T \approx \frac{g_m}{2\pi} \frac{1}{\left[C_{gs} + C_{gd}\right]\left[1 + g_{ds}\left(\underset{\uparrow}{R_S} + \underset{\uparrow}{R_D}\right)\right] + C_{gd}\, g_m \left(\underset{\uparrow}{R_S} + \underset{\uparrow}{R_D}\right)}$$

$$(4) \quad f_{\max} \approx \frac{f_T}{2\left[g_{ds}\left(R_i + \underset{\uparrow}{R_S} + R_G\right) + 2\pi\, f_T\, R_G\, C_{gd}\right]^{1/2}}$$

Seemingly R_D
- affects f_T (correct).
- does not affect f_{max} (NOT correct).

R_S and R_D should be small

Source and Drain Series Resistances



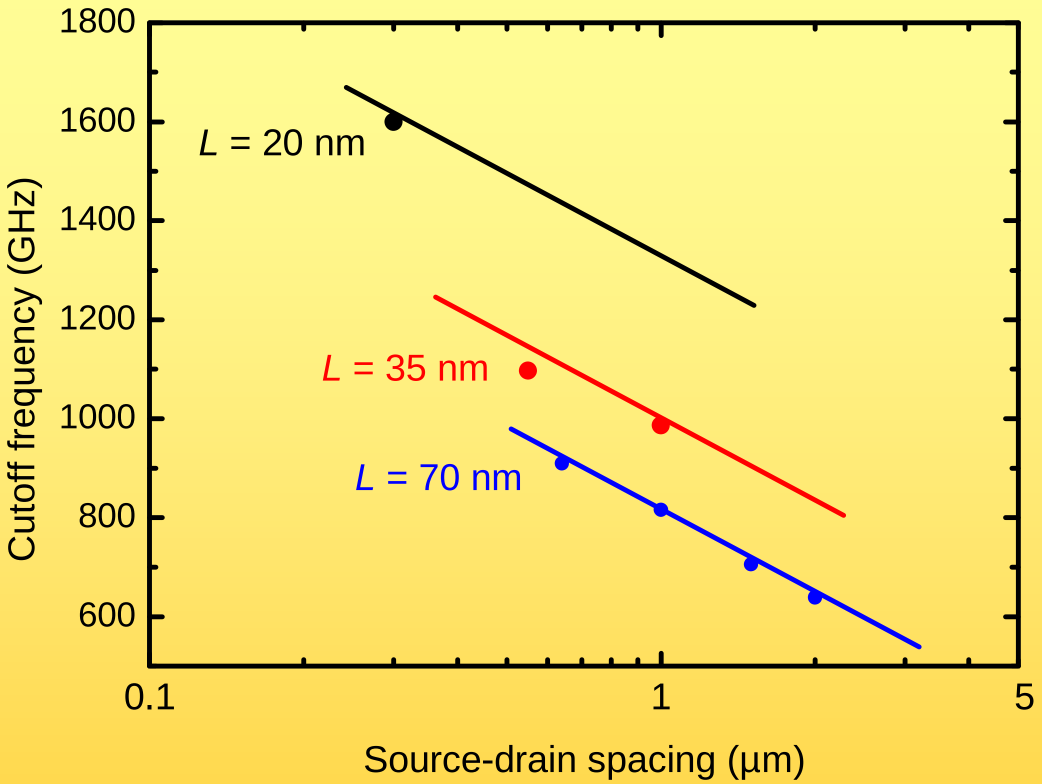
Ratio $R_{ext}/R_{channel}$ of different MOSFET generations.

Ref. S. E. Thompson et al., IEEE Trans. Semicon Manufact. 18, pp. 26-36, 2005.

R_{ext}: sum of source and drain series resistances.

"Improving external resistance appears more important than new channel materials (like carbon nanotubes) since the ratio of external to channel resistance is approaching 1 in nanoscale planar MOSFETs."

Source and Drain Series Resistances



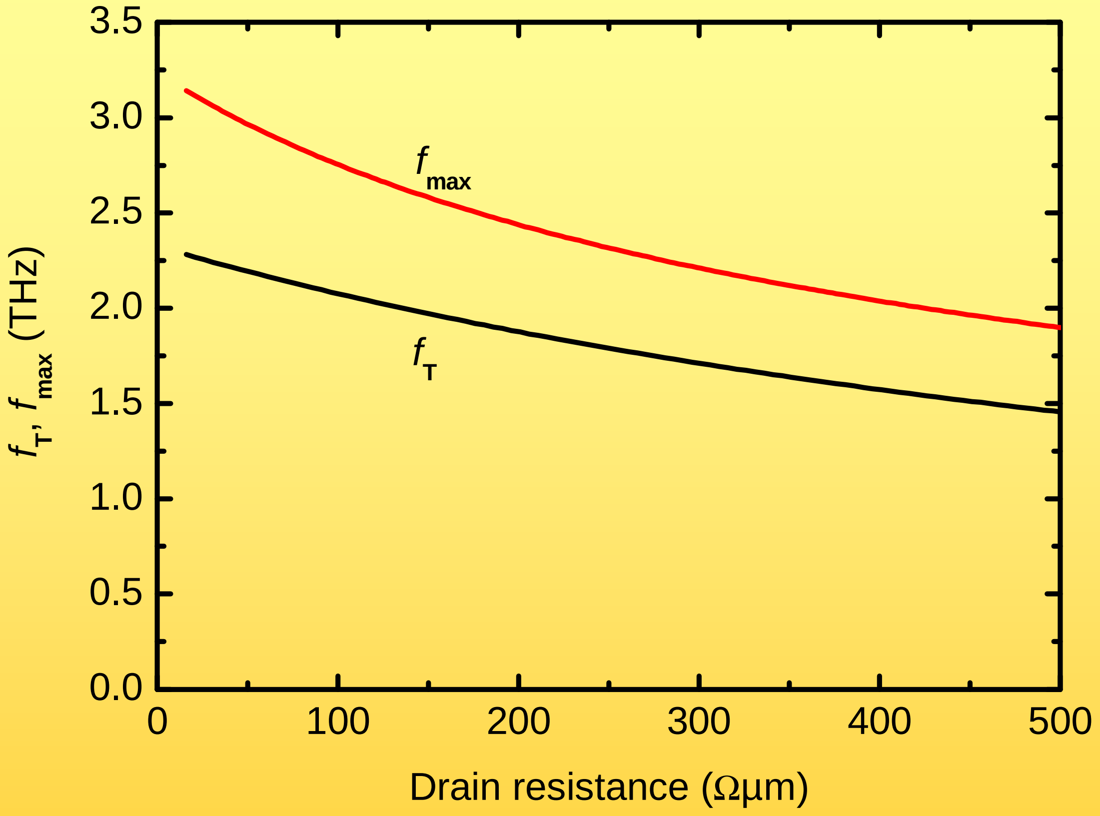
Cutoff frequency of InP HEMTs vs source-drain spacing

Ref. J. S. Ayubi-Moak et al., TED 54, pp. 2327-2338, 2007.

Large source-drain spacing for a given gate length: large R_S and R_D.

"One cannot arbitrarily reduce the gate length in hopes of dramatically improving the frequency response without also downscaling the inherent source-gate and drain-gate spacings in the proper ratio amounts along the device length."

Source and Drain Series Resistances



Simulated f_T and f_{max} of a 10-nm double-gate MOSFET.

t_{Si} 4 nm, EOT 1 nm, undoped channel, $N_{S/D}$ 2×10^{20} cm^{-3}.

Ref.: R. Granzner and F. Schwierz, TU Ilmenau, to be published.

The effect of R_D is frequently underestimated

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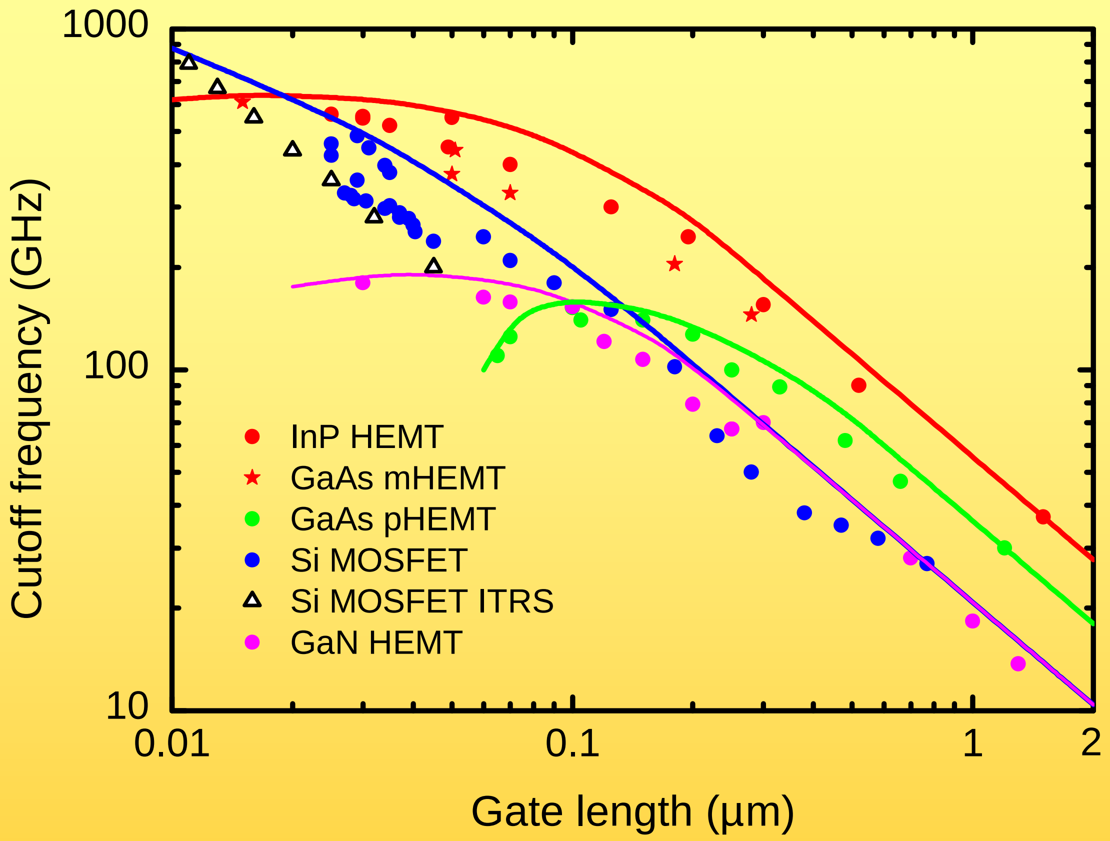
Performance of RF FETs - f_T



f_T of experimental RF FETs vs gate length

- long gates: $f_T \propto 1/L$
- short gates: f_T-L curve
  - first flattens
  - then f_T reaches maximum (GaAs pHEMT, GaN HEMT, InP HEMT, Si MOSFET)
  - finally f_T decreases with shrinking gate length

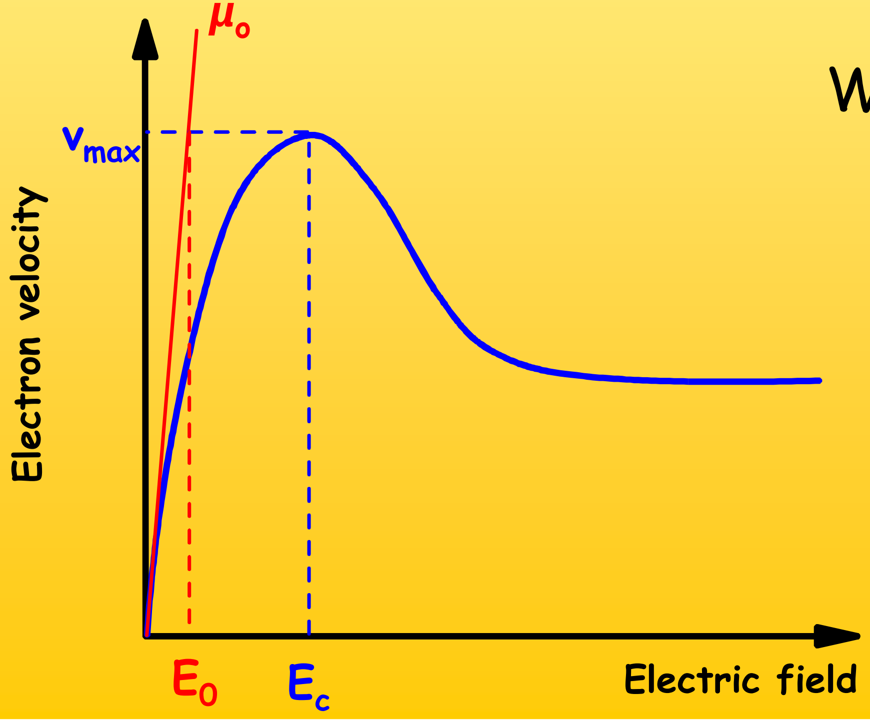
Table: f_T for different gate lengths
First number: f_T in GHz
Second number: ratio (Si MOSFET = 1)

	1 µm		100 nm		25 nm		Record early 2008	
Si MOSFET	21	1	200	1	460	1	485 (29 nm)	1
GaN HEMT	21	1	160	0.8				
GaAs pHEMT	36	1.7	160	0.8				
InP HEMTs	56	2.7	440	2.2	562	1.22	610 (15 nm)	1.26

Performance of RF FETs - f_T

Is there a connection between μ_o and f_T for long-gate RF FETs?

Material	μ_o (cm²/Vs) undoped bulk	f_T (1 μm)	BUT: μ_o in FET channel
Si	1430	21	400
GaN	1400	21	1500
$In_{0.2}Ga_{0.8}As$	9150	36	6000
$In_{0.53}Ga_{0.47}As$	13800	56	13000



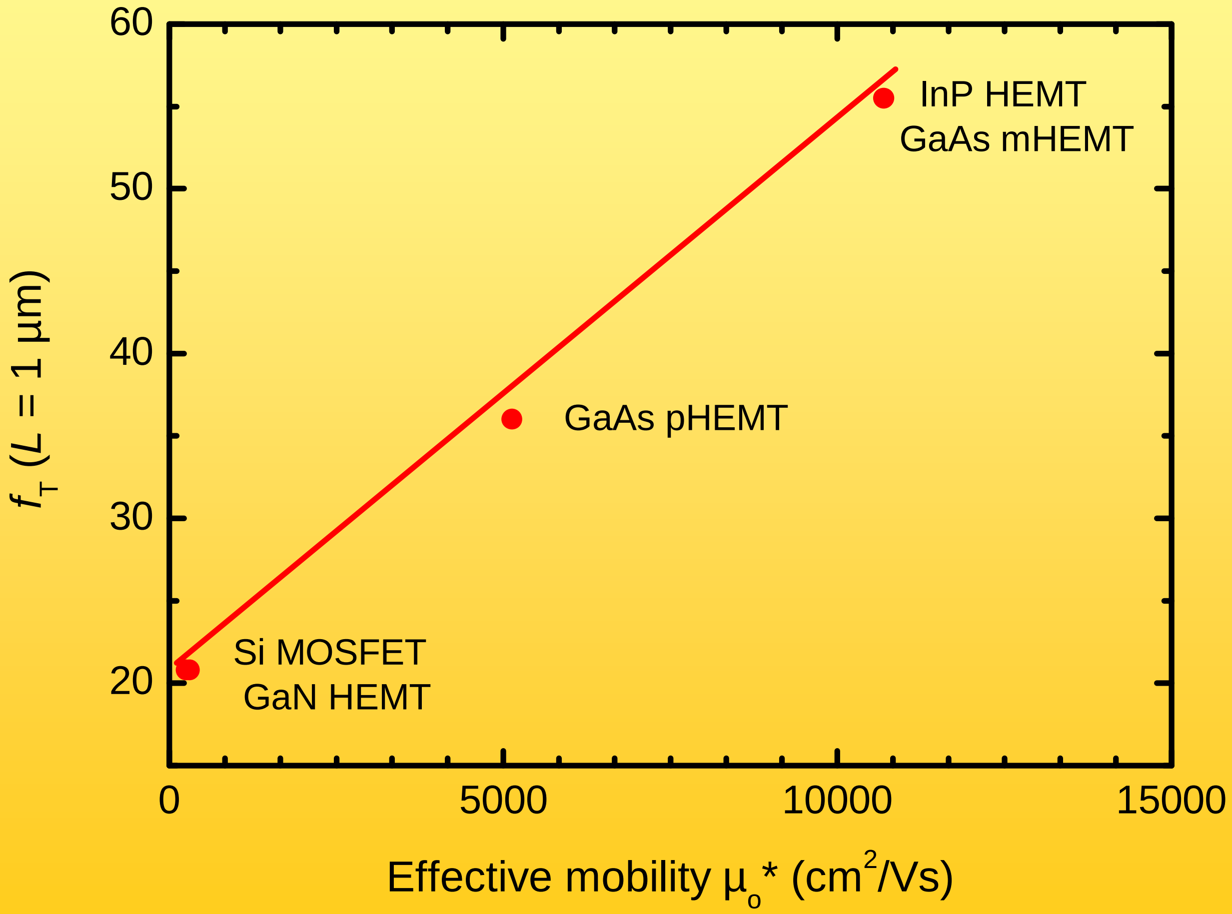
We introduce a modified mobility μ_o^*

$$E_c^* = \frac{E_0 + E_c}{2}$$

$$\mu_0^* = \frac{v_{\max}}{E_c^*}$$

Performance of RF FETs - f_T

Is there a connection between the modified mobility μ_o* and f_T for long-gate RF FETs? Seemingly yes!

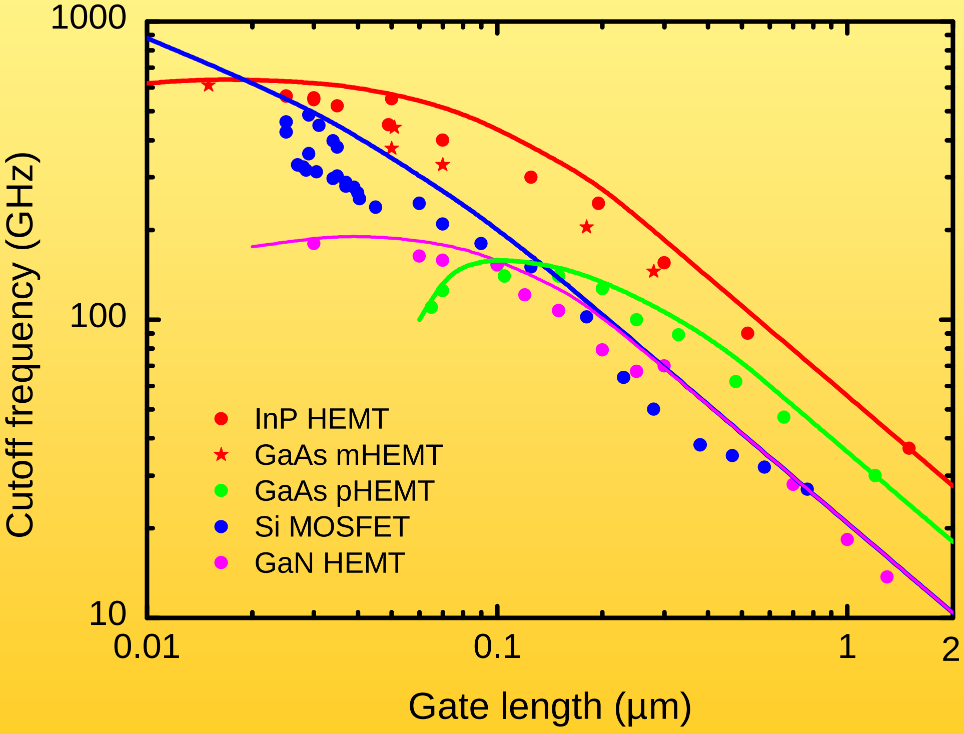


Material	μ_o*
Si	310
GaN	255
$In_{0.2}Ga_{0.8}As$	5130
$In_{0.53}Ga_{0.47}As$	10700

Performance of RF FETs - f_T

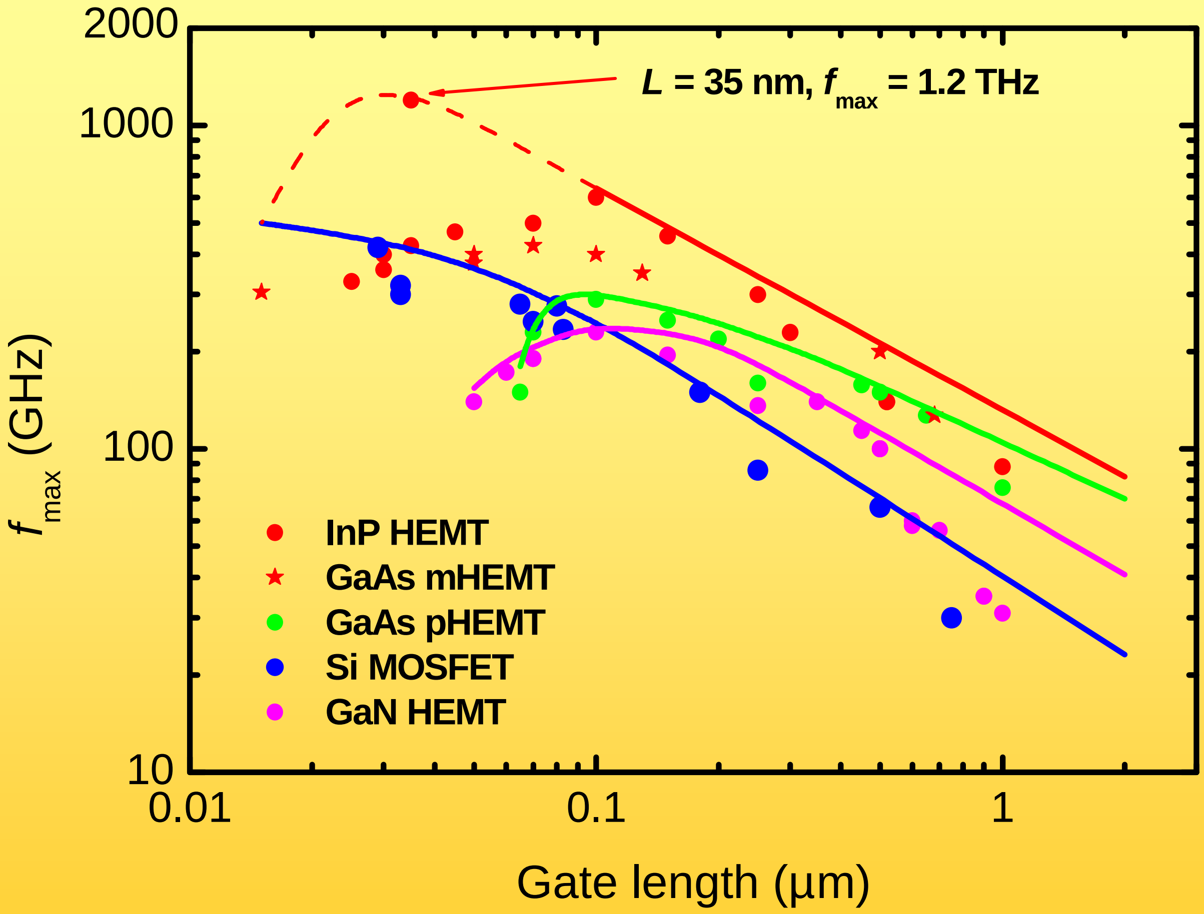
At which gate lengths the f_T–vs-L curve of a certain FET type flattens, reaches its maximum, and finally declines, depends on the strength of parasitic effects:

- short-channel effects (g_{ds})
- series resistances R_S, R_D
- gate resistance R_G
- parasitic capacitances



- GaAs pHEMTs suffer most from parasitic effects, followed by GaN HEMTs and InP HEMTs.
- Si MOSFETs are most resistant against parasitic effects.
- The Si MOSFET shows the best scaling potential.
  !! The reason is not the properties of Si but the MOSFET concept !!

Performance of RF FETs - f_{max}



f_{max} of experimental RF FETs vs gate length

Similar to the f_T-vs-L curves:

- long gates: $f_{max} \propto L^{-a}$
- short gates: f_{max}-L curve
  - first flattens
  - then f_{max} reaches maximum
  - finally f_{max} decreases with shrinking gate length

Different from the f_T-vs-L curves:

- different a for the 4 FET types
- different order of the f_{max} maximum

Again, the Si MOSFETs shows the best scaling potential !

Performance of RF FETs – Record f_T and f_{max}

Gate length (nm)	f_T (GHz)	f_{max} (GHz)	FET type	Ref.
35	520	425	InP HEMT	Watanabe, IPRM 2007
30	554	358	InP HEMT	Shinohara, IPRM 2007
25	562	330	InP HEMT	Yamashita, EDL 2002
35	385	1200	InP HEMT	Lai, IEDM 2007
16	610	305	GaAs mHEMT	Yeon, IEDM 2007
50	440	400	GaAs mHEMT	Elgaid, EDL 2005
29	485	?	Si nMOS	Lee, IEDM 2007
25	460	?	Si nMOS	Stork, VLSI Tech. 2006
29	360	420	Si nMOS	Post, IEDM 2006
31	345	?	Si pMOS	Lee, IEDM 2007
29	238	295	Si pMOS	Post, IEDM 2006
33	270	300	Si pMOS	Lee, IEDM 2005
30	180	?	GaN HEMT	Palacios, EDL 2006
60	163	157	GaN HEMT	Higashiwaki, EDL 2006
100	124	230	GaN HEMT	Palacios, EDL 2006
100	152	?	GaAs pHEMT	Nguyen, TED 1989
100	?	290	GaAs pHEMT	Tan, EDL 1990
100	151	186	GaAs pHEMT	Wada, TED 1999

Performance of RF FETs

- InP HEMTs and GaAs mHEMTs show the best RF performance (in terms of f_T and f_{max}).

- State-of-the-art Si RF MOSFETs are VERY competitive. The gap to InP HEMTs and GaAs mHEMTs becomes more and more narrow.
  - Si MOSFET technology is most matured.
  - The MOSFET concept is least vulnerable to parasitic effects.
  - In the new ITRS the Si MOSFET will be included in the Millimeter Wave (10 GHz – 100 GHz) section and tables.

- MOSFETs with higher channel mobility could show even better RF performance. Work on III-V MOSFETs has started.

- Are there further options?

Physics and Performance of Ultra-High-Frequency Field-Effect Transistors

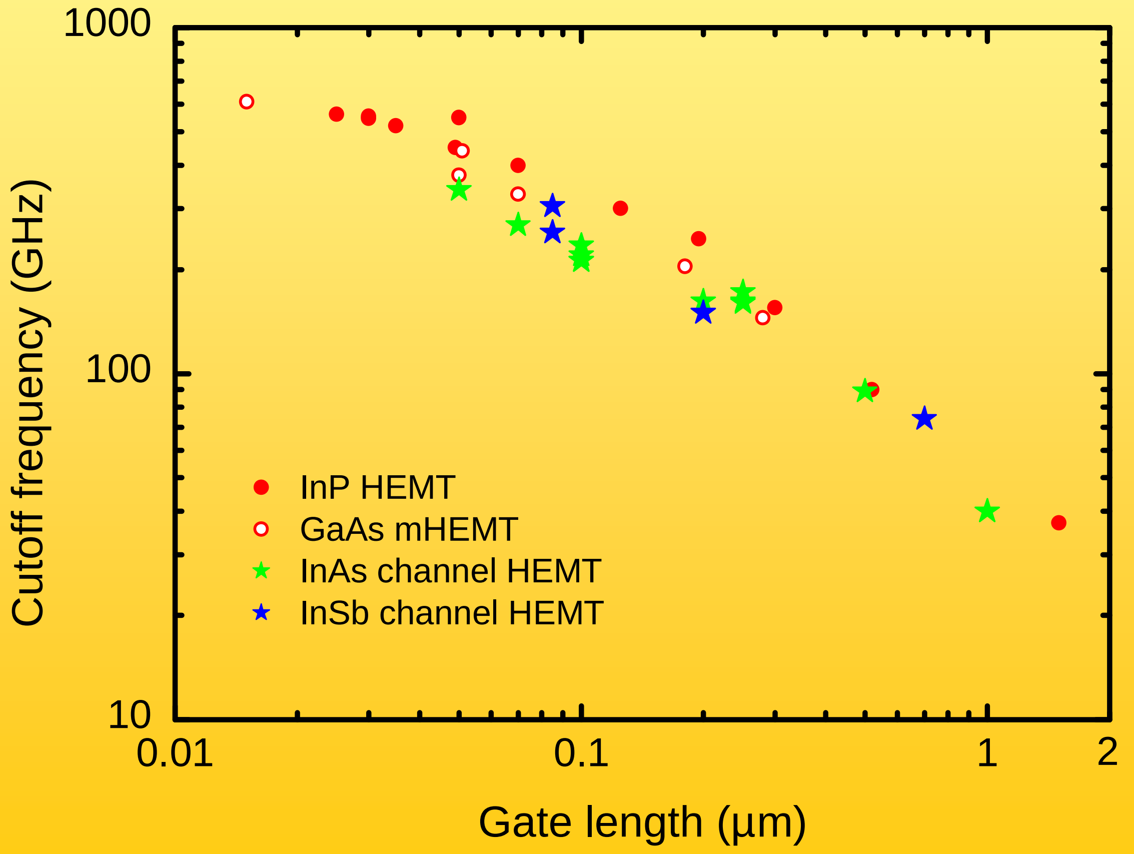
Outline

- Introduction
- RF FET Physics and Design Rules
- Performance of RF FETs
- **Options for Future RF FETs**
- Conclusion

Options for Future RF FETs - InAs and InSb

Narrow bandgap semiconductors – very high mobility

- HEMTs with InAs channel ($\mu_o \sim 25\,000$ cm^2/Vs)
- HEMTs with InSb channel ($\mu_o \sim 30\,000$ cm^2/Vs)

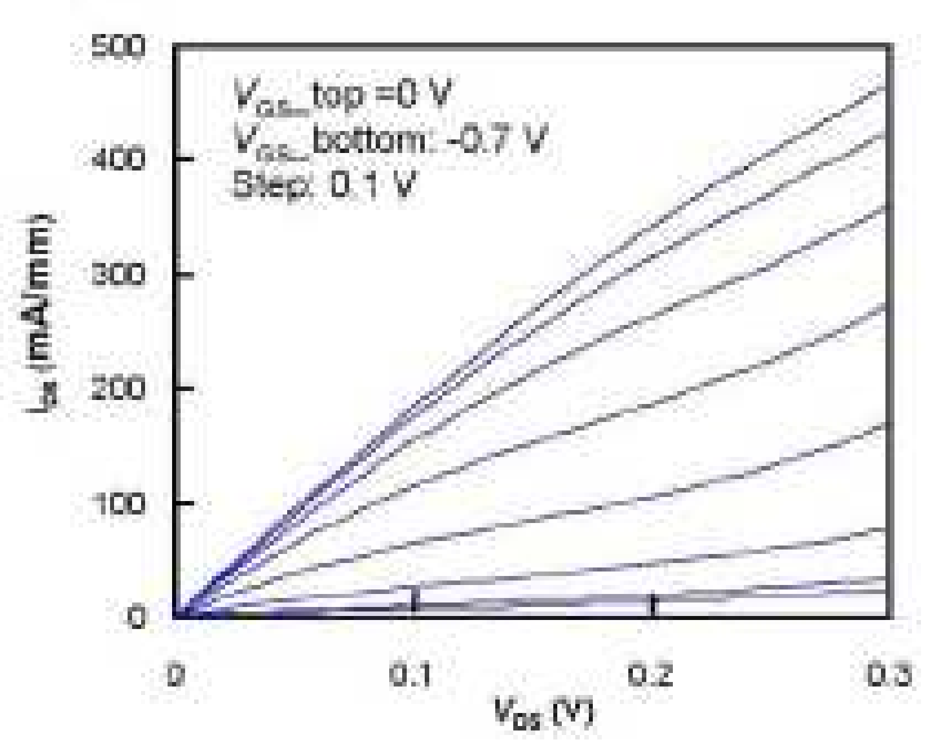


f_T vs L of experimental HEMTs with InGaAs, InAs, and InSb channels.

InAs and InSb channel HEMTs roughly follow the trend of InP HEMTs and GaAs mHEMTs

Why no advantage due to the high μ_o of the narrow bandgaps?
- technology not mature
- !! very high g_{ds} !!

Options for Future RF FETs – InAs and InSb



Output characteristics of an InAs channel HEMT (L 100 nm)

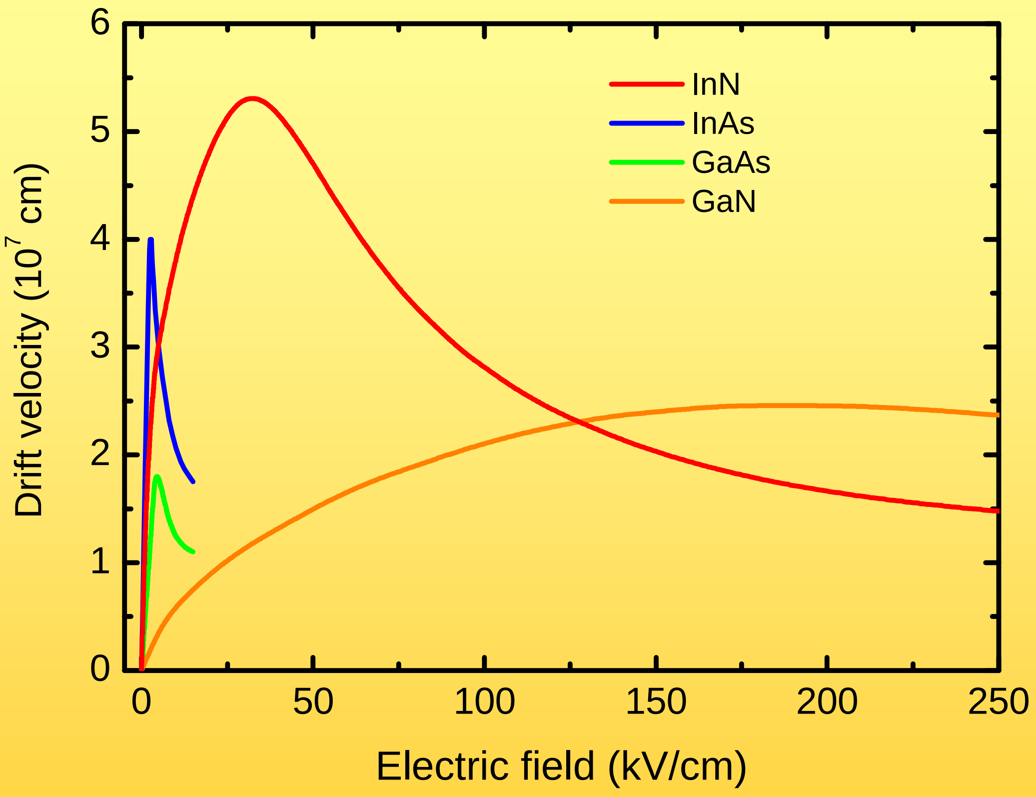
Ref.: Y. C. Chou et al., IEDM 2007, pp. 617-620.

What is the advantage of HEMTs with InAs and InSb channels?

High gain (i.e., high f_T and f_{max}) at very low V_{DS}.

Potential for ultra-low-power high-speed applications.

Options for Future RF FETs – Indium Nitride



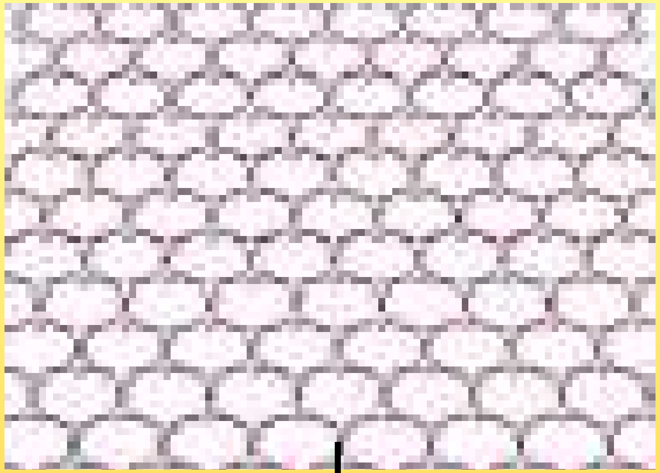
Our μ_o* model leads to an f_T for a 1-μm InN FET of ~ 30 GHz (more than Si MOSFET and GaN HEMT but less than GaAs pHEMT and InP HEMT).

InN shows unique carrier transport characteristics:

- Mobility far above 10 000 cm^2/Vs (simulated for undoped material).
- Extraordinary high peak velocity above 5x10^7 cm/s (simulated).
- Problems
  - Low quality of epitaxially grown InN (high dislocation density)
  - Maximum measured mobility only 3000 cm^2/Vs.
  - No matured InN technology. Only a few reports on operating InN devices (and only dc) so far.

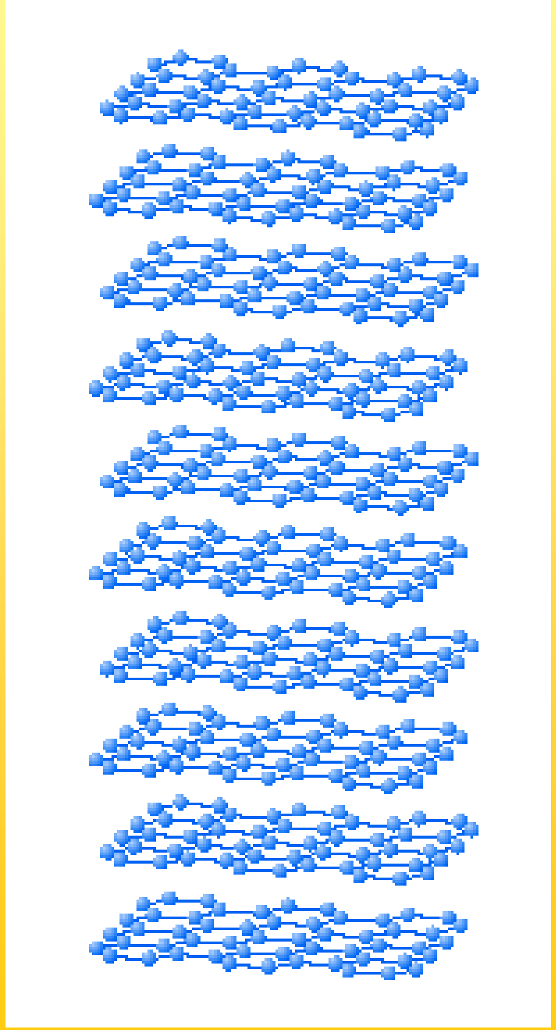
Options for Future RF FETs - Carbon

Carbon for RF FETs: Graphene and carbon nanotubes
Carbon atoms arranged in a two-dimensional honeycomb lattice: graphene.

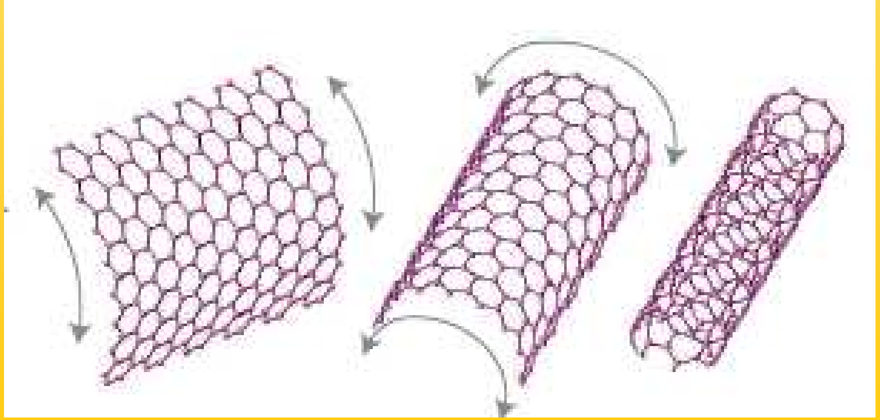


Graphene

Stacked into
3D graphite

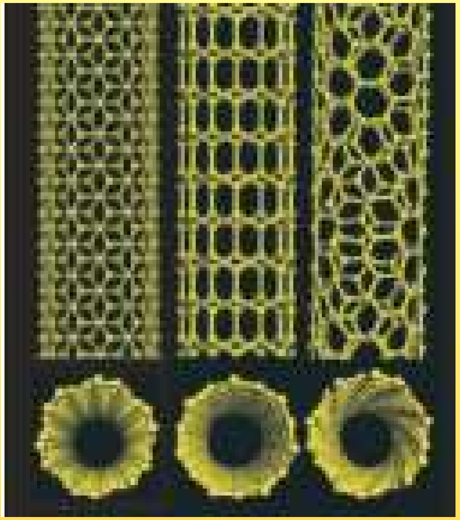


Rolled into
1D nanotubes



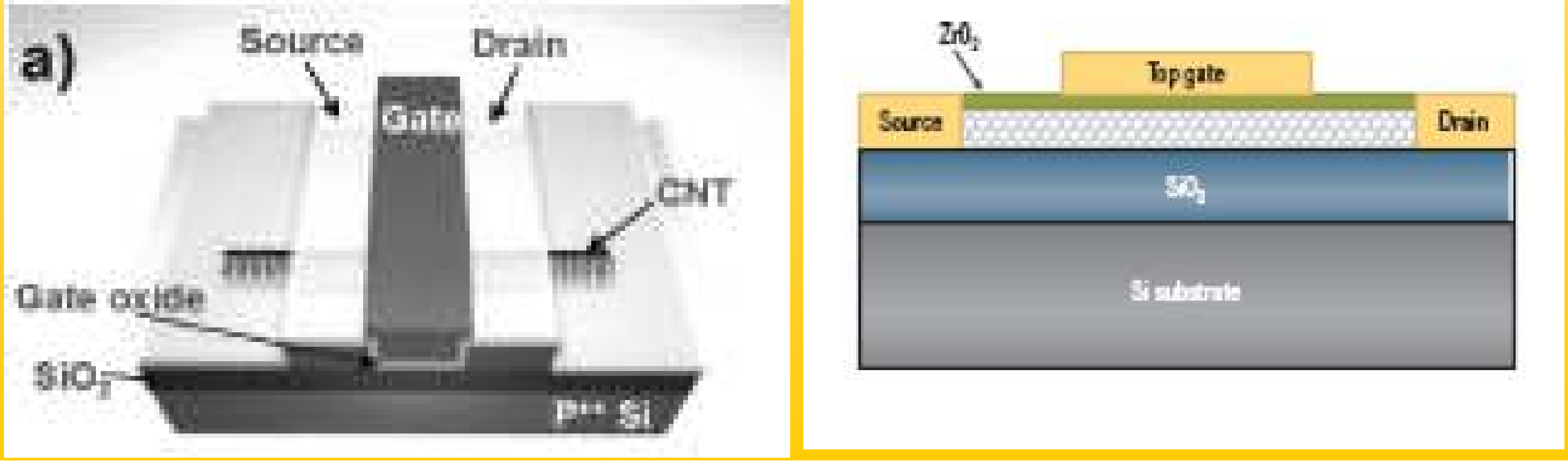
Options for Future RF FETs: CNT FETs

Depending on how the graphene is rolled (e.g., zigzag-type), the CNT may be semiconducting (small diameter – large bandgap) or metallic.

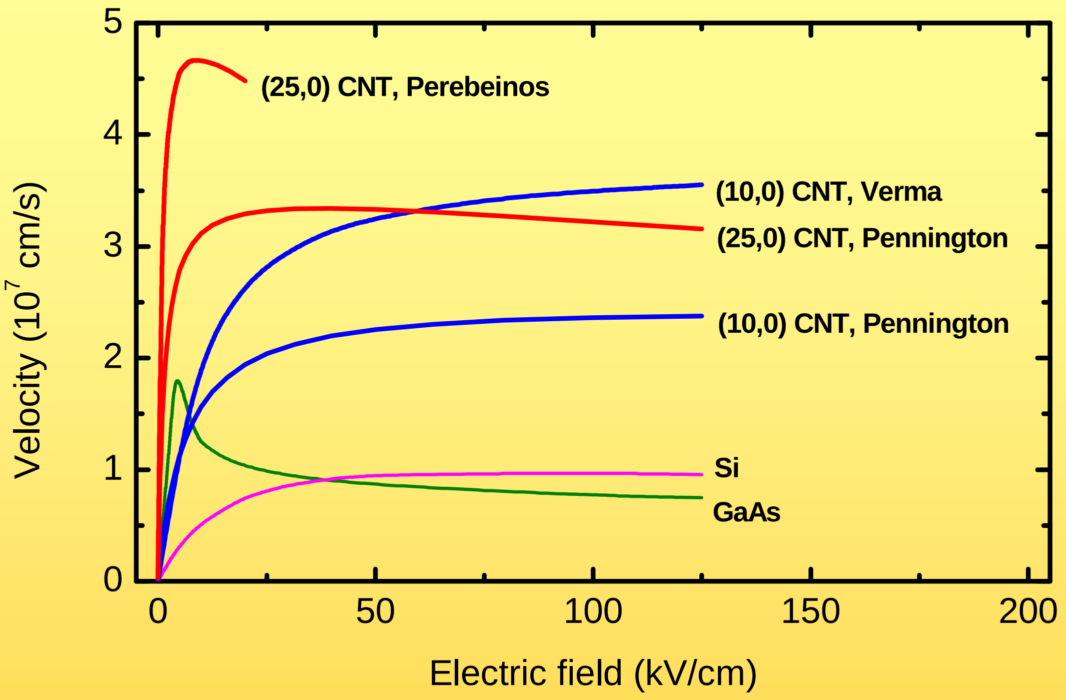


Different types of CNTs
left: armchair
middle: zigzag
right: chiral
Ref.: R. H. Baugham et al., Science 297, pp. 787-792 (2002).

Possible structure of a CNT MOSFET
Refs.: P. Avouris et al., Proc. IEEE 91, pp. 1772-1784 (2003).
R. Martel, Nature Mat. 1, pp. 203-204 (2002).



Options for Future RF FETs: CNT FETs



Simulated electron v-E characteristics for CNTs.

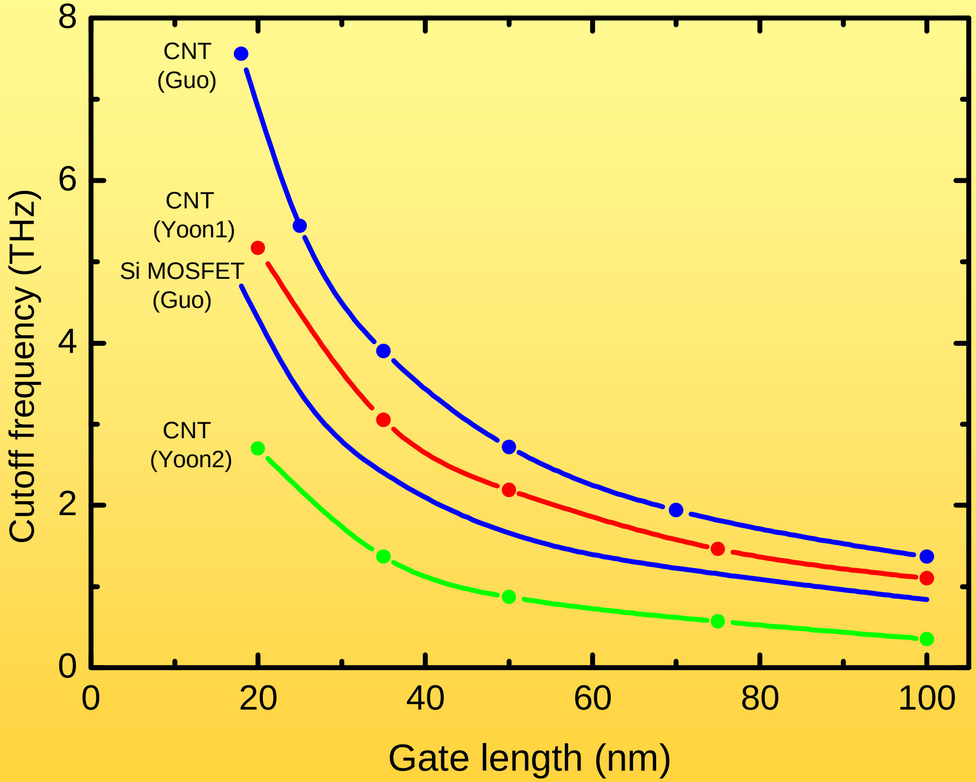
Note:

- The simulated results for identical tubes differ considerably.
  Refs.: A. Verma, JAP 97, 114319, 2005.
  V. Perebeinos, PRL 94, 086802, 2005.
  G. Pennington, Phys. Rev. B 68, 045456, 2003.
- CNT MOSFETs with promising DC characteristics have been reported.
- First RF results have been published.
  see, e.g.: D. Wang, IEEE Trans. Nanotechnol. 6, pp. 400-403, 2007.

- CNTs show extremely very mobilities and maximum/peak velocities.
- The promising carrier transport characteristics, combined with the MOSFET concept, make CNT FETs attractive for future RF applications.
- Note, however, that
  - the enthusiasm about CNT FETs during late 1990s and early 2000s has faded.
  - several of the most pressing problems of CNT technology could not be solved.

Options for Future RF FETs - CNT FETs

Simulated f_T of CNT FETs



CNT (Guo)
- (22,0) CNT, d = 1.7 nm, E_G = 0.5 eV
- Ballistic case (no scattering)

Si MOSFET (Guo)
-Ballistic case

CNT (Yoon1)
- (17,0) CNT, d = 1.33 nm, E_G = 0.63 eV
- ballistic case

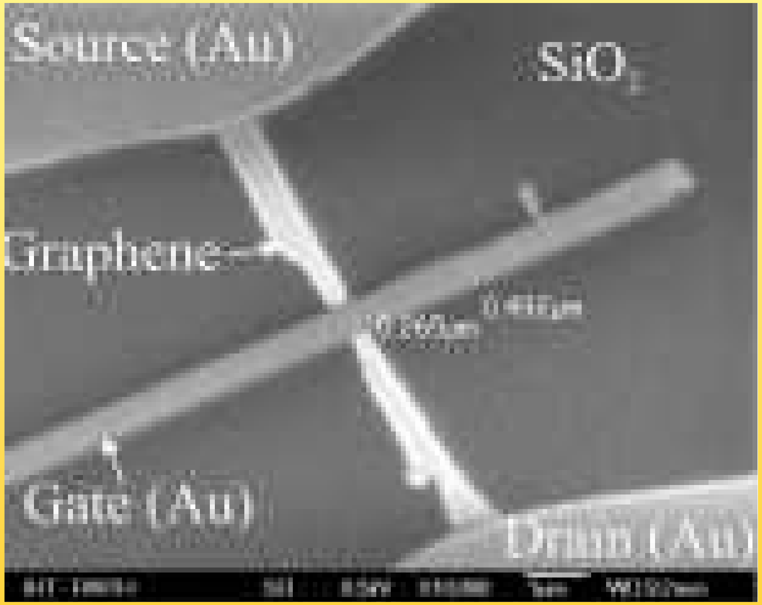
CNT (Yoon2)
- (17,0) CNT
- nonballistic case, scattering included

The RF potential of CNT FETs is promising.
Note: simulated f_T's are usually MUCH higher than experimental ones.

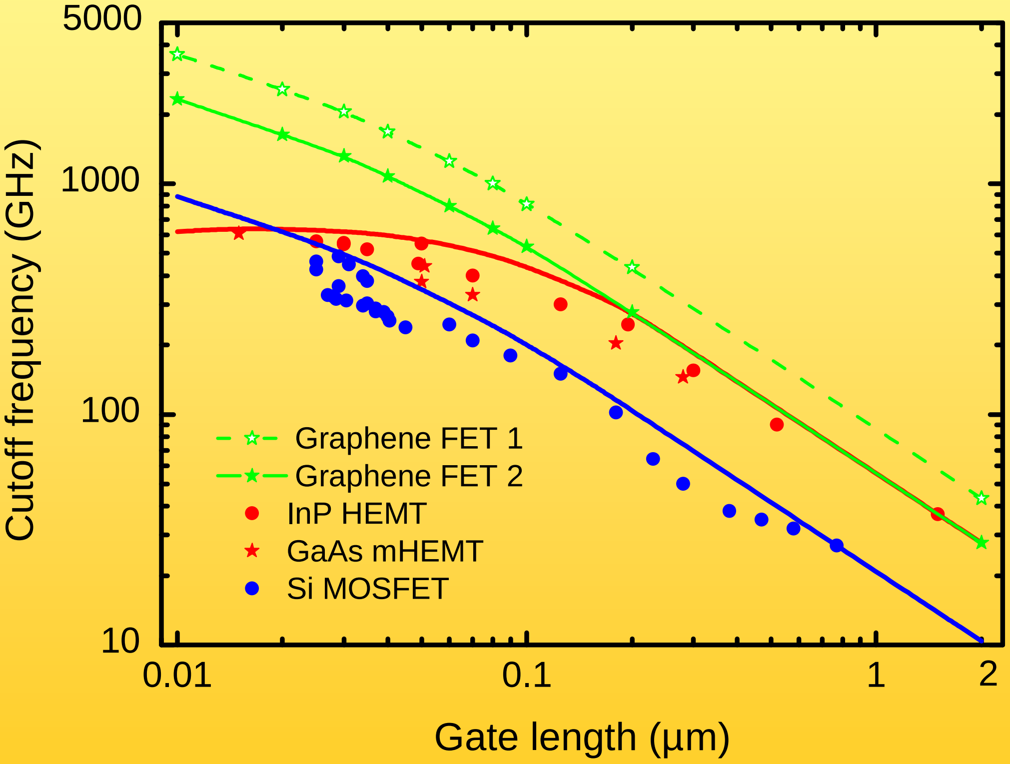
Refs.:
Guo: J. Guo et al., IEEE Trans. Nanotechnol., 4, pp. 715-721, 2005.
Yoon: Y. Yoon et al., TED 53, pp. 2467-2470, 2006.

Options for Future RF FETs – Graphene FETs

Graphene: – very high mobilities have been measured (> 15 000 cm^2/Vs at 300 K)
- no data on high-field transport
- first MOSFET has been reported (M. Lemme, AMO, Germany)
- Intel, IBM, ST, and others are also active



First experimental graphene FET with top gate.
M. Lemme et al., EDL Apr 2007, AMO Aachen, Germany



An intuitive estimation of the speed potential (f_T) of graphene FETs

Options for Future RF FETs – Graphene FETs

Reasons for optimism regarding graphene FETs:

- – Mobilities > 15 000 cm^2/Vs at RT have been measured in graphene.
- - If sources of disorder (impurities, ripples) can be eliminated, RT mobilities of 200 000 cm^2/Vs are predicted.

  Ref.: S. V. Morozov et al., PRL 100, p. 016602, 2008.
- - Channel thickness 1 atomic layer – superior electrostatics, extremely small scale length (e.g. Λ_1), short FETs with effectively suppressed short channel effects should be possible)
- - DARPA program for RF graphene FETs: CERA - Carbon Electronics for RF Applications. Goal: Graphene FETs with f_T, f_{max} > 500 GHz.

Reasons for scepticism regarding graphene FETs:

- - So far, the high mobility of graphene layers could not be transferred to FET channels.
- - Large area graphene behaves near-metallic (zero bandgap).
- - The current hype on graphene is similar to the enthusiasm regarding CNTs a few years ago.
- - No technology for large-area graphene preparation available.

Conclusion

- Currently, the fastest RF FETs are
  - InP HEMTs and GaAs mHEMTs
  - Si MOSFETs
  - GaAs pHEMTs and GaN HEMTs.
- The MOSFET concept shows considerable advantages compared to the HEMT concept.
- A high mobility is desirable but NOT sufficient for good RF performance at short gate length levels. Note: Mobility is related to stationary transport. Effects like velocity overshoot and ballistic transport have not been covered in our discussions.
- In nm-gate RF FETs, parasitic effects (short-channel effects, series resistances, etc.) become more and more important.
- Possible future options:
  - III-V MOSFETs
  - InN FETs
  - CNT FETs, Graphene FETs.
- Carbon-based RF FETs are very promising, BUT: many problems have to be solved and many questions need to be answered.